Georgia Institute of Technology
STATE ENGINEERING EXPERIMENT STATION
Atlanta, Georgia

PROGRESS REPORT NO. 19

PROJECT NO. 98

FOOD PRESERVATION

Prepared for

TENNESSEE VALLEY AUTHORITY

By

F. BELLINGER and T. W. KETHLEY

JULY 1 - SEPTEMBER 30, 1948

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I. SUMMARY

This report presents the results of work carried out on the development of methods for the characterization of the physical condition of green beans; the determination of the thermal characteristics of peach flesh at low temperatures, and of Irish potato flesh and green beans at elevated temperatures; studies on leakage results obtained from frozen strawberries and peach slices under various conditions; and on the experimental use of color prints in the study of color changes in foods.

As the previous work on the determination of leakage from frozen fruits and berries had shown such promise, similar studies were attempted on frozen green beans. These were unsuccessful, but the estimation of the free water content of thawed green beans by means of drying rate determinations was found to be of possible value in characterizing the physical condition of green beans. A significant difference was observed between the drying rates for blanched green beans and those for frozen and thawed green beans when the drying rate was determined as per cent weight loss per minute in a stream of air at 150° F.

Further studies were made on the use of penetrometer tests in characterizing the physical condition of green beans. It was found that a punch test, whereby the weight required to force a blunt needle through the pods of green beans is measured, yields more reproducible data than does the penetrometer test employing a sharp needle. Furthermore, the punch test is more sensitive to changes in the physical condition of green beans than is the penetrometer test in determining the maturity or freshness of these beans.

The thermal diffusivity of peach flesh was determined, as a result of further experiments in heat transfer in the unsteady state, to be 0.00465 and 0.00415 ft^2/hour for the temperature ranges 80°-32° F. and 80°-0° F., respectively. These values were found to be in agreement with those previously determined for water, Irish potato flesh, English peas, and strawberries for these temperature ranges. As a basis for the calculation of the time-temperature relationships involved in blanching, the thermal diffusivity of Irish potato flesh and of green beans was determined for the temperature range 80°-180° F. These values were found to be 0.0076 ft^2/hour for green beans and 0.0061 ft^2/hour for Irish potato flesh.

Studies on the leakage from strawberries frozen at different rates and stored for periods of three and six months showed that samples frozen in such a manner that the temperature of the sample passed through the zone of crystallization in ten minutes or less exhibited a greater increase in leakage following storage for the first three months than did those samples frozen at slower rates. However, the more rapidly frozen samples did not show an increase in leakage due to the storage for three months following the initial storage of three months, whereas the more slowly frozen samples did show an increase in leakage.

A considerable amount of work was accomplished on the study of the effect of various factors on the leakage obtained from frozen peach slices, some 1500 samples being frozen for this purpose. It was found that the more fresh and succulent peaches are prior to freezing, the greater will be the difference between the leakage values obtained from frozen peach slices frozen quickly and those obtained from peach slices frozen slowly.

In general, the condition of peaches prior to freezing was found to have a significant effect on the leakage of samples of frozen peach slices. Preliminary experiments were carried out to determine the effect of the temperature to which peach slices are cooled on the leakage obtained, but the results were too conflicting to permit the formulation of any conclusions. The results of studies made on the effect of variation of the storage temperature of frozen peach slices indicate that the length of storage may have a greater effect in increasing the amount of leakage obtained from frozen peach slices than large variations in storage temperature, providing the variation in temperature is not great enough to permit thawing of the peach slices.

Intensive work on the possible use of color prints in studying color changes in foods has led to the conclusion that this method is not practical for this purpose.

II. EXPERIMENTAL WORK

A. Investigations on the Physical Characteristics of Green Beans.

1. Drying Tests.

The work carried out on the determination of leakage from fruits and berries had shown such promise that it was believed worthwhile to consider some method of determining leakage from vegetables such as green beans. Attempts to apply the technique employed for the determination of leakage from fruits and berries to the determination of leakage from green beans were unsuccessful due to the small quantity of leakage involved. Because of the small amount of fluid lost by frozen beans during the thawing process, errors were magnified to such an extent that it was impossible to obtain reproducible data. However, it was felt that the freezing process does cause a shift in the location of a certain amount of the water contained in green beans, and that it might be possible to determine the extent of this shift by measuring the rate at which frozen and thawed beans lost moisture when subjected to drying tests. This was postulated on the basis of the theory that part of the damage caused in foods by freezing is due to the collapse of small amounts of the colloidal gel, thus shifting some of the total water content from the bound state to the free state. In fruits and berries, which have thin cell walls, this free water leaks out of the cells and is of such quantity that it can be measured with some accuracy. In vegetables which have thick cell walls and large numbers of starch granules which take up water quickly, moisture which has been freed by the collapse of colloidal gels does not readily pass beyond its normal location. However, if the collapse of a certain amount of gel causes an increase in the amount of free water in the vegetable,

it should be possible to estimate this increase by determining the relative ease with which water is removed from these vegetables.

Drying in the ordinary laboratory oven was not considered because of the great amount of time consumed by this method. A comparison of methods of accelerated drying such as by the use of vacuum and forced air indicated that forced air drying would be most useful for the determination of the rate of moisture loss from vegetables, due to the ease with which individual weighings could be made during the drying process. A Dietert rapid drier was therefore secured for this purpose, and studies were initiated on the rate of moisture loss of green beans. This drier consists of a blower, thermostatically controlled heating elements, and a perforated metal cup in which the sample to be dried is placed and through which the warm air is forced by the blower. It was first necessary to determine the optimum temperature of the air for the drying test. It was decided that the temperature of the air should be the lowest possible which would permit the partial drying of the samples within a reasonable length of time. Too high a temperature could possibly cause interference with the purpose of the test by cooking the sample and changing its physical characteristics.

Frozen green beans from the same lot were removed from 0° F. storage, thawed, and 50.0-gram samples weighed out in preparation for determining the drying rate. For these determinations, the temperature of the drier air was at various times 230°, 220°, 210°, 185°, 175°, 160°, and 150° F. A minimum of three determinations was made for the samples in each condition by placing the weighed sample in the drier cup with the blower and heater in operation, and removing the cup and sample every five minutes

for a weighing. This process was continued until the weight loss per weighing became small enough to indicate that the sample was essentially dehydrated. In this manner data were collected from which it was possible to construct a family of curves, plotting per cent moisture loss against time in minutes for various air temperatures. As the shape of these curves was the same in all cases, being distinguished only by the increasing moisture loss per unit of time with increasing temperature, the lowest temperature in the series (150° F.) was selected for further investigations because this temperature is not high enough to cause coagulation of the tissue of vegetables.

During the course of these preliminary experiments a large amount of variation was observed in the results obtained from triplicate determinations. Investigation showed that this was primarily due to uneven heating of the samples in the metal cup because of the high thermal conductivity of the metal cup and the low thermal conductivity of the beans. A temperature differential of as much as 60° F. was observed between the cup and the sample. Thus, a sample in which the beans were cut in such lengths that the majority of the sample was touching the bottom of the cup would heat up more rapidly than would a sample in which the beans were piled on each other. In order to correct this condition, a perforated ceramic cup was substituted for the metal one. The ceramic cup was made from a small Buchner funnel by cutting off the stem and throat. This cup and the drier are shown in Figure 1. Using this cup and an air temperature of 150° F. it was found possible to obtain reproducible data on the moisture loss of green beans in periods of time as short as ten minutes.

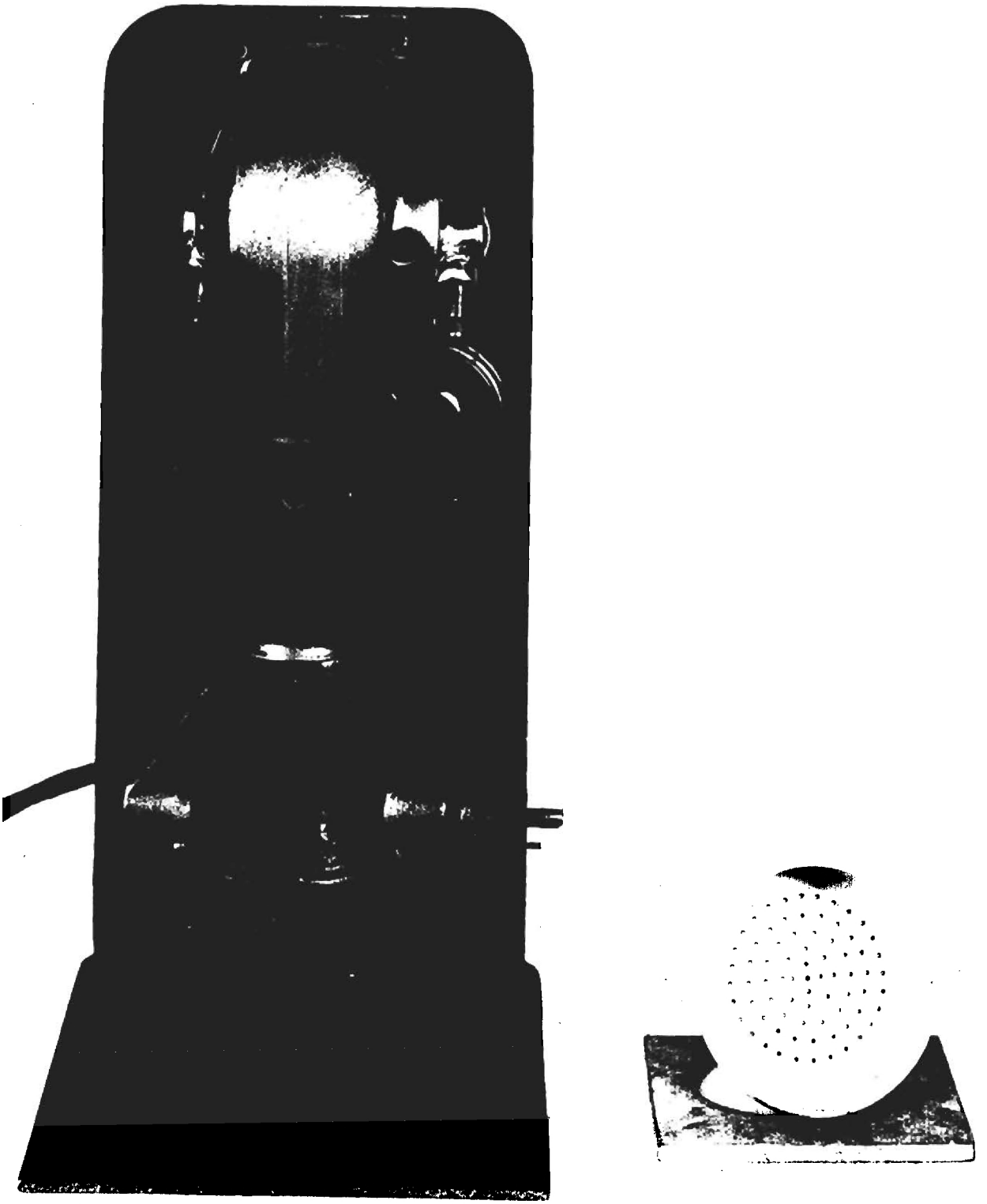


Figure 1. Drier and Ceramic Cup Used for the Determination of the Drying Rate of Green Beans.

After establishing ten minutes at 150° F. in a ceramic cup as tentative conditions, a check was made on certain other factors which might affect the values obtained. Because the primary interest was in frozen foods, the effect of the length of time between the removal of the sample from 0° F. storage and the introduction of the sample into the drier was investigated. Two groups of frozen green beans were removed from storage, and at various times following this removal were used for tests in the drier. The results of these tests are shown in Table I.

TABLE I

THE EFFECT OF VARYING THE LENGTH OF TIME FROZEN SAMPLES ARE HELD AT ROOM TEMPERATURE BEFORE DETERMINING MOISTURE LOSS, ON THE PER CENT MOISTURE LOSS OF GREEN BEANS

Sample No. 1		Sample No. 2	
Time Lapse, Hours Between Removal from Storage and Drier Test	Moisture Loss Per Cent, Due to Ten Minutes Drying at 150°F.	Time Lapse, Hours Between Removal from Storage and Drier Test	Moisture Loss Per Cent, Due to Ten Minutes Drying at 150°F.
1.0	8.4	1.0	7.4
1.5	9.0	1.5	6.9
2.0	8.8	2.0	6.9
2.5	9.4	2.5	7.6
3.0	8.0	3.0	7.1

The results shown in Table I indicate that there is no significant difference in the results obtained from the partial drying of frozen green beans whether they are left to thaw for one hour or three hours. Thus, no

very exact control on the amount of thawing time should be necessary in carrying out drying tests.

In order to determine whether or not blanched samples would dehydrate rapidly at room temperature and thus cause a variation in the drier test because of variations in the time lapse between blanching and partial drying, a series of determinations similar to those carried out on the frozen samples was performed on blanched green beans. It was found that no significant variation existed in the results obtained from partial drying of the blanched samples as long as the time between blanching and the running of the drier test was not less than 30 minutes and not longer than two hours. Raw beans were also exposed for this same period of time, and no difference in moisture loss due to the exposure time was obtained.

Although the tests on frozen beans and on blanched beans had indicated that as much as two hours variation in the time lapse between the removal of the frozen sample from 0° F. storage or the completion of the blanching process and the initiation of the drying test did not affect the determination, it was considered possible that this apparent lack of variation might be due to a change in the total moisture content of these samples. This point was checked by determining the total moisture content of raw, blanched, and frozen green beans by drying samples of these at 230° F. to constant weight. Among a number of samples the per cent total moisture ranged from 91.2 to 92.4, no significant difference due to processing being found. It was therefore concluded that samples of beans in each of the three conditions of interest, namely, raw, blanched, and frozen (and then thawed), can be held for as much as two hours at room temperature prior to the determination of the drying rate without affecting that

determination. It was further concluded that blanched samples should be allowed to cool for 30 minutes and that frozen samples should be allowed one hour for thawing prior to the determination of drying rates.

Having determined the time limits for the handling of samples, a series of runs was made to determine more exactly the minimum time necessary for accurately calculating the drying rate of green beans in an air stream at 150° F. The results of this experiment are shown in Table II.

TABLE II

VARIATION IN MOISTURE LOSS FROM GREEN BEANS WITH VARIATION IN TIME OF EXPOSURE TO AIR STREAM AT 150° F.

Time of Exposure, Minutes	Moisture Loss, Per Cent*		
	Raw Beans (n=5)**	Beans Blanched in Boiling Water (n=3)**	Beans Frozen in Air (n=7)**
10	4.8 ± 0.2	7.2 ± 0.4	9.0 ± 1.0
15		11.1 ± 0.8	13.5 ± 1.0
20		14.7 ± 0.4	17.7 ± 1.3
25		17.9 ± 0.9	21.4 ± 1.0

*Determined by placing samples in stream of air at 150° F., after the samples had stood at room temperature for one hour.

**"n" equals number of determinations.

Examination of the data in Table II shows that the rate of drying expressed as per cent of moisture lost per minute is a little better than 0.7 for the blanched samples for 10, 15, 20, and 25 minutes exposure and about 0.9 for all the times shown for frozen samples. These facts indi-

cate that rate of drying can be determined for green beans under these conditions with equal accuracy for exposure times varying from 10 to 25 minutes. It would seem that it would be advantageous to use the longer period of time for those samples which have a relatively low rate of drying and the shorter period of time for samples which have a higher rate of drying. In any event, the results will be comparable so long as they are expressed in the same terms, namely, per cent per minute.

It should be noted that a significant difference between the results obtained from the raw, water blanched (in boiling water), and frozen beans exists in the data shown in Table II. In order to check the validity of these data in the case of steam blanching, another group of determinations was run on a second batch of beans, using ten minutes exposure time for the calculation of the drying rate. The data for steam blanched, raw, and frozen beans are shown in Table III.

TABLE III

THE DRYING RATE FOR GREEN BEANS UNDER VARIOUS CONDITIONS

Drying Rate, Expressed as Per Cent Loss Per Minute in Air Stream at 150° F.			
Raw Beans (n=5)*	Beans Blanched in Steam (n=12)*	Beans Frozen (Thawed Two Hours)	
		Quick-Frozen (n=13)*	Slow-Frozen (n=12)*
0.49 ± 0.016	0.51 ± 0.024	0.72 ± 0.033	0.75 ± 0.092

*"n" equals number of determinations.

It should be noted that there is no significant difference between the drying rate shown in Table III for raw beans and that for steam-blanched beans. Furthermore, there is no significant difference between the drying rates for beans frozen by the two methods of freezing, although there is a significant difference between the drying rates for the blanched as compared with the frozen. These findings confirm previous expectations that blanching in boiling water causes considerably more damage to vegetables than does blanching in steam and that the freezing processes employed do cause a slight but significant amount of damage to vegetables such as green beans.

In the course of the investigations on the physical characteristics of green beans it was reported in Progress Report 15 that the penetrometer studies gave results which showed a significant difference between raw beans and blanched beans but no difference between blanched beans and frozen (and then thawed) beans. The penetrometer test is presumed to characterize the texture of the beans, whereas the drying test should characterize the increase in the free water in the tissues of the beans. It is therefore worth noting that the data in Tables II and III show that a significant difference exists between the results obtained from the drying tests on both steam and water blanched beans and the results obtained on similar beans which had been frozen. It would therefore appear that both water and steam blanching causes changes in the texture of green beans, possibly by altering the rigidity of the cell walls, but steam blanching does not cause any significant increase in the amount of free water in green beans. On the other hand, it appears that the freezing process does cause a slight but significant increase

in the amount of free water in green beans.

It is therefore concluded that the determination of the drying rate of green beans should be of value in studying the effect of various storage conditions on green beans. It was finally concluded that the test which should be employed is as follows: A 50.0-gram sample of green beans is placed in a perforated ceramic cup in a Dietert Drier with the air temperature set at 150° F. The sample is left in the drier for 10-25 minutes, removed, and weighed. Rate of drying is determined by multiplying the weight loss in grams by two, dividing the result by the exact number of minutes the sample was in the drier, and expressing the quotient as per cent loss per minute. Blanched beans should stand at least 30 minutes but not more than two hours before weighing the sample and placing it in the drier. Samples to be frozen should be weighed after blanching to facilitate accurate weighing and allowed to thaw one to three hours before testing.

2. Penetrometer and Punch Tests.

In Annual Report No. 3 (pages 171-180) it was reported that tests which determined the weight necessary to force a small blunt needle through the pod of a green bean seemed to be of value in characterizing the physical condition of green beans. The apparatus used originally was cumbersome, and it was impossible to accumulate much data with it. For this reason, an investigation of other methods of determining this break-through point was made. Correspondence with research workers interested in the texture of such diverse materials as bread, pickles, and lard showed that the possibility of determining the break-through point of these materials as an index of the texture had been given some consider-

ation. Mr. G. T. Carling of the Swift and Company laboratories in Chicago, Illinois, was the only individual who had made any definite progress in this work. He has developed a "bread-biter" which forces a hollow cylinder of metal through a slice of bread and measures the force required to cut through.

It was suggested that measurement be made of the force exerted by the bean, rather than that applied to the bean, or, as in the case of the "bread-biter," to the bread. Several layouts were tried using variations of the penetrometer but none seemed to show any promise, so some tests were made using a small platform scale. The results of these tests were so satisfactory that they were continued. The scale finally used as shown in Figure 2 is a Toledo "No Springs" platform model such as used in grocery stores. This instrument reads full scale of two pounds in 0.5-ounce increments. When weights greater than two pounds are to be measured, additional weights are added to the back of the balance so that the scale remains sensitive to 0.5 ounce.

In making punch tests the following technique was found to be most simple: A green bean was held in place on the platform of the scale by means of a laboratory rubber tubing clamp mounted on a block of wood, the blunt needle was forced through the bean by hand, and the maximum rise of the weighing arm noted. The weight of the clamp and wooden block having been tared previously, the maximum reading was, therefore, the weight required to force the needle through the pod of the green bean. The needle finally used for these tests was a short section of piano wire 0.071 inch in diameter (music wire gauge 28), attached to a slightly larger brass handle. The end of this wire which was pushed or punched through the bean

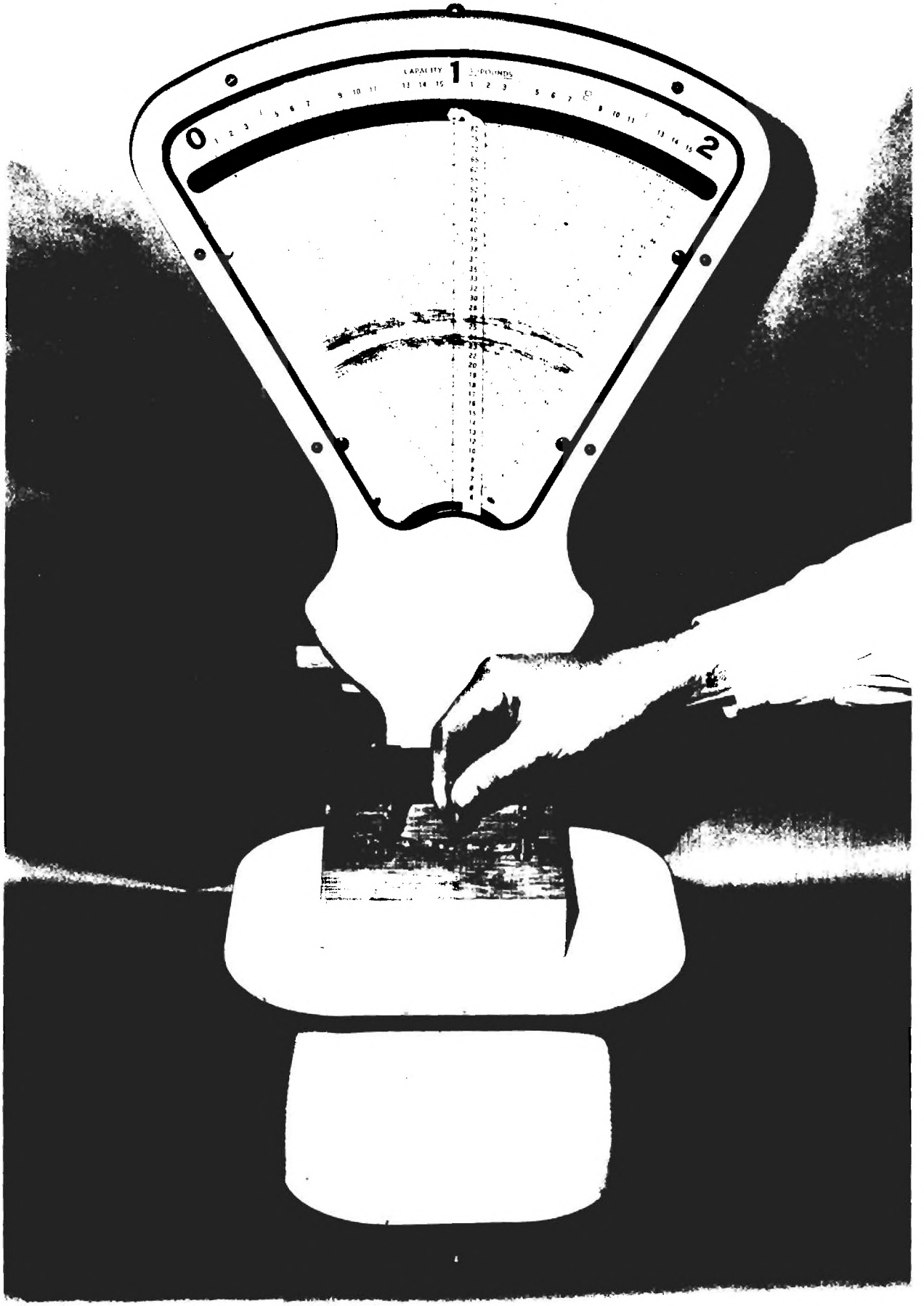


Figure 2. Toledo Scales Used in Making Punch Tests on Green Beans.

was machined flat.

Preliminary tests which were made in order to determine the point on the bean pod where the punch test would give the most reproducible readings showed that the punch should be made directly over a bean seed. The seed apparently furnished support to the pod so that the punches penetrated the pod with fair uniformity. Using this technique, a group of determinations was made on a lot of green beans which were divided according to size (small, medium, and large), in order to calculate the reproducibility of the method. Three punches were made on individual green beans, five beans constituting a sample. The average and standard deviations for the determinations on individual beans, and the average and standard deviations for the 15 punches are shown in Table IV. These data are shown only for the small and medium size beans as there was an insufficient number of large beans in this particular lot. The data are shown for the beans raw, blanched (in boiling water), and blanched (in boiling water) and frozen (in air, slowly), both for the first day the beans were obtained and for the following day. That is to say, the beans were blanched or blanched and frozen on the first day, and also on the second day.

Examination of the data in Table IV shows that the punch test results from the individual green bean exhibit no more variation than that exhibited by 15 determinations on five beans. This means that there is a variation within the individual bean equal to and not significantly greater than the variation among individual green beans, and that, therefore, random sampling of the bean is satisfactory for this test.

TABLE IV

PUNCH TESTS* ON ONE- AND TWO-DAY-OLD GREEN BEANS, WHICH HAD THEN BEEN PROCESSED, COMPARING THE VARIATION OF INDIVIDUAL BEANS WITH THE OVER-ALL VARIATION

Condition of Beans	Lot No.	Ounces Required To Penetrate Bean Pods in Punch Tests			
		Small Beans		Medium Sized Beans	
		Average of Individual Beans	Average of 15 Determinations	Average of Individual Beans	Average of 15 Determinations
Raw	1	41.5 ± 1.54		54.5 ± 2.62	
	2	39.0 ± 3.14		52.5 ± 3.50	
	3	38.3 ± 2.08	41.4 ± 3.09	58.7 ± 2.02	55.3 ± 3.18
	4	43.0 ± 1.00		57.0 ± 1.32	
	5	43.0 ± 1.81		53.7 ± 2.84	
Blanched**	1	18.0 ± 1.00		26.3 ± 2.52	
	2	17.8 ± 1.61		24.5 ± 0.50	
	3	17.5 ± 0.71	18.1 ± 1.35	26.2 ± 0.30	24.1 ± 2.88
	4	19.0 ± 2.00		22.0 ± 4.36	
	5	18.0 ± 1.73		21.5 ± 1.32	
Blanched and Frozen;*** Thawed	1	11.4 ± 1.85		11.7 ± 2.95	
	2	13.9 ± 3.10		17.3 ± 2.49	
	3	11.0 ± 2.40	14.1 ± 2.78	17.7 ± 1.80	17.6 ± 6.5
	4	15.5 ± 2.50		13.3 ± 2.32	
	5	12.2 ± 0.93		28.0 ± 5.29	
Raw (24 hours older than above)	1	42.7 ± 3.06		54.7 ± 3.06	
	2	47.7 ± 0.58		49.7 ± 1.55	
	3	48.3 ± 2.70	45.1 ± 3.07	60.3 ± 4.57	51.4 ± 6.39
	4	43.0 ± 1.73		45.7 ± 4.93	
	5	44.0 ± 1.73		46.7 ± 2.52	
Blanched**	1	19.3 ± 0.58		19.7 ± 0.58	
	2	19.0 ± 2.64		21.0 ± 1.00	
	3	19.0 ± 0.00	19.7 ± 1.33	22.3 ± 3.84	21.9 ± 2.58
	4	20.7 ± 0.58		26.0 ± 1.73	
	5	20.7 ± 0.58		20.3 ± 0.58	
Blanched and Frozen;*** Thawed	1	18.3 ± 1.6		22.0 ± 1.0	
	2	15.3 ± 1.4		20.3 ± 3.0	
	3	14.0 ± 1.7	17.6 ± 3.6	15.3 ± 1.0	18.6 ± 6.7
	4	19.0 ± 1.0		21.3 ± 6.0	
	5	14.3 ± 1.6		12.0 ± 0.0	

*The weight in ounces required to force a 0.071 inch diameter flat end steel needle through the pod of a green bean.
**Boiling water blanching process used in all cases where beans were blanched.
***Slow frozen in still air.

The averages for the 15 determinations shown in Table IV for the various conditions of the beans are included in Table V with further data obtained from punch tests made on green beans. All values shown in Table V are the averages for 15 punches, made three each on five green beans. Each average is accompanied by its standard deviation.

Three different lots of beans were used in these determinations. Unfortunately, the exact time in hours elapsed between picking and processing could not be determined exactly; it is therefore possible that there was as much as 12 hours difference in age among these three lots.

Although the number of lots of beans examined were only three, and only one of these was tested for three successive days, it appeared that the data in Table V showed the punch test to be capable of indicating differences in the physical condition of green beans. In order to test this statement thoroughly, it will be necessary to carry out tests in a location where green beans in various stages of maturity are readily available and where it will be possible to ascertain the exact time lapse following picking. Such examinations may well show the punch test to be of value in determining the maturity and lapse of time following picking of string beans. Also, since this test does give results which seem to be caused by differences in physical condition of green beans, it should be useful in detecting the changes in green beans caused by blanching, freezing, and storage.

In order to compare the results of punch tests with those from penetrometer tests, fresh green beans and lima beans were secured, steam blanched, and then frozen both slowly and quickly. The slow-frozen samples were frozen by placing blanched samples in the 0° F. storage room.

TABLE V

RESULTS OF PUNCH TESTS* ON GREEN BEANS IN VARIOUS CONDITIONS

Condition of the Beans	Bean Lot No.	Ounces Required to Penetrate Bean Pods in Punch Tests		
		Small Beans	Medium Size Beans	Unselected Beans
Fresh				
Raw	1	41.4 ± 3.1	55.3 ± 3.2	
	2	28.1 ± 3.0	36.3 ± 6.7	
	3			37.6 ± 4.2
Blanched**	1	18.1 ± 1.4	24.1 ± 2.9	
	2	12.0 ± 2.1	14.0 ± 2.9	
	3			18.7 ± 2.6
Blanched & Frozen,*** Thawed	1	14.1 ± 2.7	17.6 ± 6.4	
	2	10.4 ± 2.2	14.4 ± 4.4	
	3			16.3 ± 3.2
One Day Old				
Raw	1	45.1 ± 3.1	51.4 ± 6.4	
	2	27.3 ± 3.6	40.3 ± 9.3	
Blanched**	1	19.7 ± 1.3	21.9 ± 2.6	
	2	13.0 ± 3.1	14.7 ± 2.4	
Blanched & Frozen,*** Thawed	1	17.6 ± 3.6	18.6 ± 6.7	
	2	10.5 ± 2.1	14.4 ± 4.0	
Three Days Old				
Raw	1	37.4 ± 3.1	36.0 ± 3.5	
Blanched**	1	12.5 ± 1.7	15.7 ± 3.1	
Blanched & Frozen,*** Thawed	1	13.0 ± 3.6	14.5 ± 1.5	

*The weight in ounces required to force a 0.071-inch diameter flat-end needle through the pod of a green bean. All values shown are averages for 15 punches run three each to five beans.

**Boiling water blanching process used in all cases where beans were blanched.

***Slow frozen in still air.

About five hours was required for freezing. The quick-frozen samples were frozen in rapidly agitated alcohol at 0° F., three minutes being required for freezing.

Punch tests were run on the raw and on the blanched beans, and both penetrometer and punch tests were run on the frozen beans the day following freezing. This same day the frozen samples were removed from 0° F. storage and left 12 hours at 35° F. to permit partial thawing. These samples were then replaced in 0° F. storage, and penetrometer and punch tests were run on them the following day. All tests on the frozen beans were made after the beans had been held at room temperature two hours to allow for thawing. The results of these tests are shown in Tables VI and VII.

It is interesting to notice (1) that no significant differences are to be found in Table VI for green beans between the results of the penetrometer and punch tests for blanched, frozen, or thawed and refrozen samples and (2) that in Table VII for lima beans there are significant differences in the results of penetrometer and punch tests for the blanched, frozen, or thawed and refrozen limas. In Annual Report No. 3 (1948, p. 233), data on penetrometer tests were presented which showed a significant difference between the results obtained on both lima beans and green beans immediately after freezing and following six months storage, when the samples were allowed to thaw and refreeze during this period. Comparing these data with those in Tables VI and VII, it would appear that the damage caused by thawing and refreezing is increased by fluctuation of temperature during storage.

TABLE VI

PENETROMETER* AND PUNCH** TESTS ON GREEN BEANS IN VARIOUS CONDITIONS

Tests	Condition of Green Beans					
	Raw (Fresh)	Blanched (Steam)	Quick-Frozen		Slow-Frozen	
			Immediately after Freezing	After Partial Thawing and Refreezing	Immediately after Freezing	After Partial Thawing and Refreezing
Punch Test;*** Ounces	41.0 ± 4.5	19.5 ± 3.2	19.5 ± 3.0	20.0 ± 4.4	16.3 ± 4.0	16.4 ± 1.7
Penetrometer Test;**** Needle, 0.1 mm.			37.5 ± 8.0	40.3 ± 1.0	39.0 ± 8.3	37.2 ± 7.4

*Penetration in 0.1 mm. of the penetrometer needle into the pod of a green bean with 15 grams weight on the needle.

**The weight in ounces required to force a 0.071-inch diameter flat-end needle through the pod of a green bean.

***Average of 20 punches for each test.

****Average of 20 penetrations for each test.

TABLE VII

PENETROMETER* AND PUNCH** TESTS ON LIMA BEANS IN VARIOUS CONDITIONS

Tests	Condition of Lima Beans					
	Raw (Fresh)	Blanched (Steam)	Quick-Frozen		Slow-Frozen	
			Immediately after Freezing	After Thawing and Refreezing	Immediately after Freezing	After Thawing and Refreezing
Punch Test,*** Ounces	28.0 ± 7.0	11.5 ± 1.5	10.5 ± 1.0	8.1 ± 0.9	10.1 ± 1.3	9.0 ± 0.5
Penetrometer Test,**** needle, 0.1 mm			23.0 ± 6.7	28.0 ± 8.2	23.0 ± 6.7	26.0 ± 3.9

*Penetration in 0.1 mm. of the penetrometer needle into the pod of a lima bean with 10 grams weight on the needle.

**The weight in ounces required to force a 0.071-inch diameter flat-end needle through the pod of a lima bean.

***Average of 20 punches for each test.

****Average of 20 penetrations for each test, 10-grams weight on the needle.

In addition to the penetrometer data previously presented, ascorbic acid determinations were made on the green beans and lima beans which had thawed and refrozen (Annual Report No. 3, p. 230). These determinations had shown that there was no significant change in the ascorbic acid content of lima beans or green beans caused by thawing and refreezing. In order to check these data, samples of beans out of the same lot which was used for the penetrometer and punch tests were analyzed for their ascorbic acid content. It was found that no significant change in ascorbic acid content was caused by the thawing and refreezing process. The data for this experiment are shown in Table VIII.

B. The Determination of Thermal Characteristics of Food.

1. The Thermal Diffusivity of Peach Flesh.

The thermal diffusivity of peach flesh was determined for the temperature ranges 80° - 32° F. by the technique summarized on pages 159-162 of Annual Report No. 3. Because of the difficulty of securing thermocouples in the soft peach flesh, cut cylinders of peach flesh were fitted into the cork borers employed for cutting these cylinders, and the entire assembly was used for the freezing experiments. Previous work with potato flesh had shown that the time required to heat identical long rods of potato flesh, either enclosed in a cork borer or free, was the same in either case. It was therefore assumed that a thin metal sleeve covering the food had no perceptible effect on the determination of the thermal diffusivity of the food.

TABLE VIII

THE ASCORBIC ACID CONTENT* OF GREEN BEANS AND LIMA BEANS IN VARIOUS CONDITIONS

Method of Freezing	Ascorbic Acid Content, Mgm. per 100 Grams			
	Green Beans		Lima Beans	
	Immediately after Freezing	Following Thawing and Refreezing	Immediately after Freezing	Following Thawing and Refreezing
Slow, in Packages in Air at 0° F.	7.9	7.8	23.2	20.3
Rapid, Loose in Alcohol at - 10° F.	9.5 ± 1.0**	10.1	19.2	20.3

*Determined titrimetrically with indophenol, each value is the average of three determinations unless otherwise specified.

**Mean and standard deviation on 12 samples. This standard deviation represents a deviation of ± 10.5% around the mean and applies to all values shown in this table.

Thermocouples of No. 30 copper-constantan wire were located at the center of the rods of peach flesh, and the output of the thermocouples was measured with the high-speed temperature recorder. The results of these runs are shown in Table IX.

TABLE IX

DATA FOR THE DETERMINATION OF THE THERMAL DIFFUSIVITY OF PEACH FLESH

External Conditions	Rod* of Peach Flesh Diameter (Inches)	θ,** Seconds Temperature Range, $^{\circ}$F.		α*** $ft^2/hr \times 10^{-5}$ Temperature Range, $^{\circ}$F.	
		80°-32°	80°-0°	80°-32°	80°-0°
Well Agi-	0.60	100	260	470	400
tated Al-	0.60	95	270	490	430
cohol Bath	0.625	110	270	430	415
at -10° F.	0.625	120	270	470	415
Average				465	415

*The rod of peach flesh having a length greater than eight times its diameter, it was considered that the length was infinite for the purposes of calculation.

**θ = Time from start of cooling or heating, seconds.

***α = Thermal diffusivity constant.

It should be pointed out that the values for thermal diffusivity shown in Table IX are lower than those obtained for water, Irish potato flesh, English peas, and strawberries, the values for the latter materials running between 535-615 x 10^{-5} for 80°-32° F., and 460-563 x 10^{-5} for 80°-0° F. (Annual Report No. 3, 1948, pp. 166-167). The average apparent specific heat of peach flesh for the temperature range 80°-32° F. is 0.91 BTU/lb.$^{\circ}$ F., and for 80°-0° F. is 2.4 BTU/lb.$^{\circ}$ F. Peach flesh has a den-

sity of 68.5 lb/ft^3 at room temperature. Substituting the values for thermal diffusivity, density and apparent specific heat into the equation for thermal conductivity: $k = \alpha \rho c_p$, a value of 0.290 BTU/(hr)(ft^2)($^\circ$F./ft) is obtained for the thermal conductivity of peach flesh over the temperature range 80°-32° F. This value is of the expected order, comparing favorably with the value of 0.35 BTU/(hr)(ft^2)($^\circ$F./ft) for water in this temperature range. Similarly, estimating the average density of peach flesh to be about 65 lb/ft^3 in the temperature range 80°-0° F., a value of 0.65 BTU/(hr)(ft^2)($^\circ$F./ft) is obtained for the apparent average thermal conductivity of peach flesh in this particular temperature range. This compares with the value of 0.72 BTU/(hr)(ft^2)($^\circ$F./ft) for the apparent average thermal conductivity for water for the same temperature range.

2. The Thermal Characteristics of Irish Potato Flesh and of Green Beans.

In Annual Report No. 3 (1947, p. 163), the data for the determination of the thermal characteristics of Irish potato flesh at temperatures as low as 0° F. were reported. More recently, data have been collected on the thermal characteristics of Irish potato flesh and green beans at temperatures as high as 180° F. This information is to be used in calculating the time-temperature relationships involved in the blanching of vegetables. The work involved in the collection of the experimental data was carried out in part by two students as a special problem for scholastic credit. Their report in full is attached to this progress report as Appendix A.

The actual experiments were carried out using No. 30 chromel-alumel thermocouples located at the center of long cylinders of either potato flesh or green beans. Chromel-alumel couples were used because of the

rigidity of such wires and because of the lower thermal conductivity of these metals (as compared to copper and constantan). The output of the thermocouples was recorded on the high-speed temperature recorder, using the temperature of boiling water and of melting ice for calibration purposes. In order to reduce the electrical resistance of the thermocouple circuit, short leads of No. 30 wire were used for the couple, and longer leads of No. 18 wire were used to connect these to the amplifier.

After the insertion of the thermocouple into the sample, the sample was suspended in a moist chamber (covered liter beaker half-filled with water) at room temperature until thermal equilibrium was reached. The sample was then immediately removed to the proper conditions where the time-temperature history of the center of the sample was recorded. Three sets of conditions were employed for these experiments: (1) the samples were suspended freely in a steam compartment (free flowing steam) maintained at 212° F., (2) the samples were laid on a tray of No. 8 mesh aluminum screen in the steam compartment maintained at 212° F., and (3) the samples were suspended in a bath of actively boiling water at 212° F. The complete report on this study is shown in Appendix A. A summary of the data is given in Table X.

TABLE X

THE AVERAGE THERMAL DIFFUSIVITY OF IRISH POTATO FLESH AND GREEN BEANS FOR THE TEMPERATURE RANGE, ROOM TEMPERATURE TO 180° F.

Conditions of the Experiment	Values for Irish Potato flesh		Values for Green Beans	
	m*	α **	m*	α **
Samples Suspended in Steam at 212° F.	0	6.14 ± 0.45***	0	7.58 ± 1.01****
Samples on Aluminum Screen in Steam at 212° F.	0.12	6.11 ± 0.97***	0	8.50 ± 1.05***
Samples Suspended in Actively Boiling Water at 212° F.	0	6.13 ± 0.44***	0.17	8.04 ± 1.23*****

*Estimated values. Dimensionless.
**Thermal diffusivity. $(Ft^2/hr)10^{-3}$.
***Average of five determinations.
****Average of six determinations.
*****Average of eight determinations.

It will be noted that the values for thermal diffusivity in Table X were calculated for m equal to zero for the samples suspended in steam. This value of m was selected because this condition had the highest coefficient of heat transfer of the three used in these experiments. The radii of the samples (0.325 inch or less) were small enough so that the assumption that m would be zero for any well agitated bath was open to question. It was therefore assumed that m would be zero for the condition of the highest coefficient of heat transfer, and a graphical estimation of m for the other two conditions was made on the basis of the thermal

diffusivity calculated from the data obtained in the steam bath. Examination of the estimated values for m shown in Table X shows that m was taken to be zero for the green beans on a metal tray, but not for the potato samples on metal trays. That m was taken to be zero was because of the larger size of the potato samples, permitting the interfering effect of the screen mesh on free circulation to affect the data obtained. This difference in size would also account for the fact that m was assumed to be zero for potatoes in a boiling water bath, but not for green beans.

The values for thermal diffusivity shown in Table X appear to be consistent with the prior assumption that the thermal characteristics of vegetables are similar to those of water. The thermal diffusivity of water, calculated from the average specific heat, thermal conductivity, and density ($\alpha = \frac{k}{\rho c_p}$) in the temperature range, room temperature to 180° F., is 6 x 10^{-3} ft^2/hr, which is identical with those obtained for Irish potato flesh in this temperature range. The nonhomogenous structure of string beans could easily account for the fact that the values obtained for the thermal diffusivity of this vegetable were somewhat different.

The values obtained for the thermal diffusivity of Irish potato flesh and for green beans were employed for the estimation of the thermal conductivity of these foods, using the average specific heat and density for the temperature range as shown in Annual Report No. 3 (1948, pp. 166-167). The thermal conductivity for string beans was estimated to be 0.46 BTU/(hr)(ft^2)(°F./ft) and for Irish potato flesh to be 0.35 BTU/(hr)(ft^2)(°F./ft).

C. The Relationship Between the Time Required for Freezing and the Amount of Leakage of Strawberries.

The data obtained from leakage tests run on strawberries frozen in various lengths of time were reported previously (Annual Report No. 3, 1948, pp. 187-198). The data shown there were for tests made immediately after freezing and following three months storage at $0^{\circ} \pm 0.5^{\circ}$ F. These samples were held in storage under these conditions for six months and then used for further leakage tests. The results obtained are shown in Table XI. All leakage determinations were made by the method shown in Annual Report No. 3 (1948, pp. 220-221).

TABLE XI

LEAKAGE VALUES FOR STRAWBERRIES FROZEN UNDER VARIOUS CONDITIONS AND STORED AT $0^{\circ} \pm 0.5^{\circ}$ F. FOR SIX MONTHS

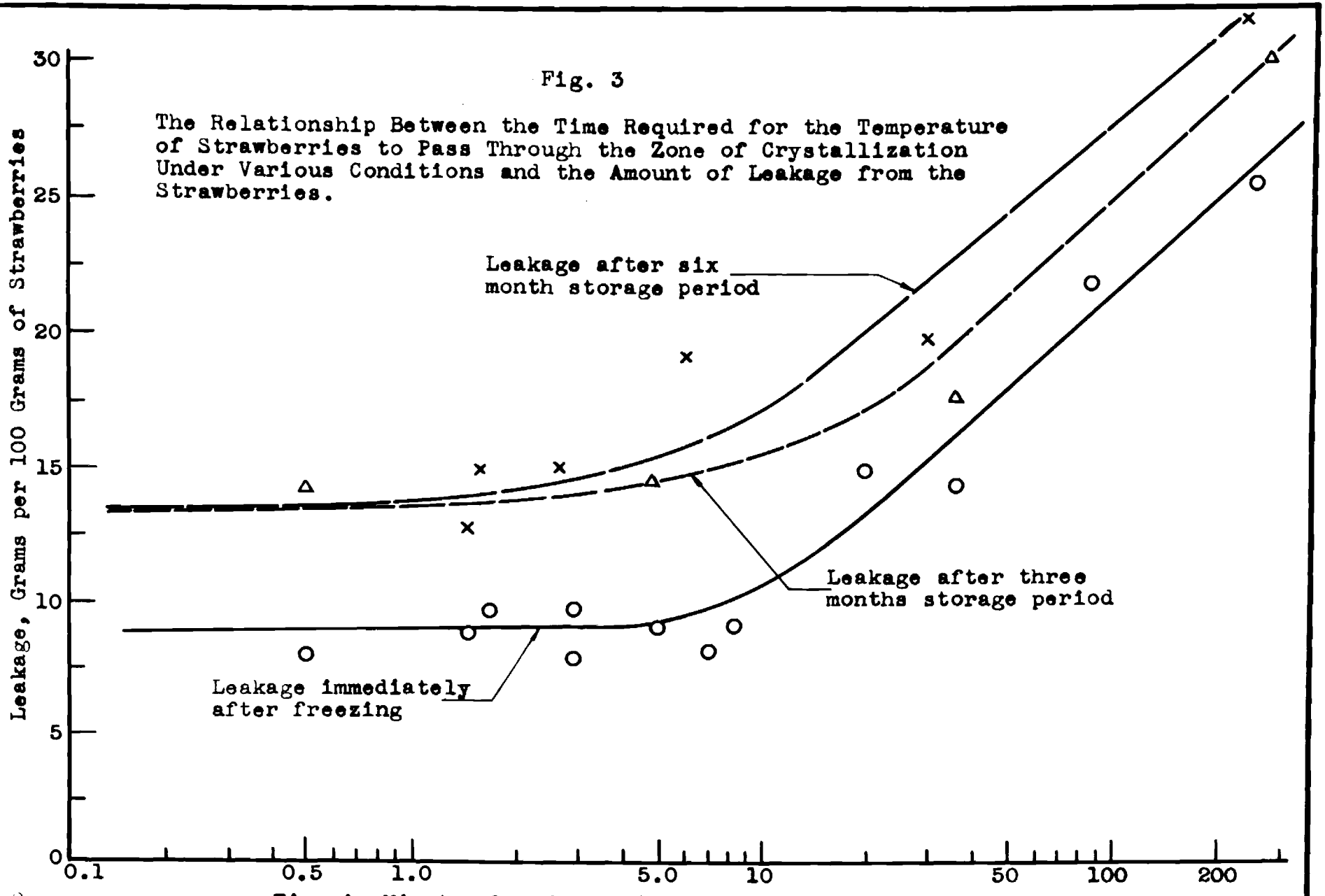
Time Required for Temperature of Berry to Pass Through the Zone of Crystallization, in Minutes	Leakage*, Grams per 100 Grams of Strawberries
1.5	12.6
1.6	14.4
3.0	15.0
7.0	18.2
45.0	17.8
260.0	33.0

*Leakage was determined by weight loss when berries were left for four hours in mineral spirits at 68° F. All values shown are averages for triplicate determinations, having a standard deviation of $\pm$ 20%.

The data for leakage values obtained from the strawberries immediately after freezing, after three-month storage period at $0^{\circ} \pm 0.5^{\circ}$ F., and after a six-month storage period at $0^{\circ} \pm 0.5^{\circ}$ F. are plotted in Figure 3.

Fig. 3

The Relationship Between the Time Required for the Temperature of Strawberries to Pass Through the Zone of Crystallization Under Various Conditions and the Amount of Leakage from the Strawberries.



It can be seen that the samples which leak the least (those in which the temperature passed through the zone of crystallization in ten minutes or less) showed the greatest per cent increase in leakage after the three-month storage period, and the leakage for these samples remained essentially the same between three and six months storage. On the other hand, the samples in which the temperature passed through the zone of crystallization in more than ten minutes showed a linear increase of leakage with an increase in storage time. It thus appears that there is a potential damage limit as reflected by the leakage determination, and, as this is approached, the tendency for the damage to be increased by further storage time diminishes.

D. Printon.

During the past three months, emphasis has been placed on determining whether or not it is possible to utilize Printon for reproducing the natural colors of foods in order to have a medium through which color changes could be shown to other workers in this field. It was finally concluded that it is impossible to use Printon for this purpose because of the difficulties encountered in the Georgia Tech laboratory in preparing exact color reproduction. Because of the necessity of handling foods in season, little work was accomplished during the spring and summer of 1948 on the possible use of Printon, the most recent work having been reported in Annual Report No. 3 (1948, pp. 125-129). These investigations have been pursued along the lines laid down at that time, and a large number of color prints have been made.

Transparencies were prepared of a number of different subjects: green beans, lima beans, peaches, strawberries, color-plaques, and color

perception charts (used to test for color blindness). These transparencies were then used to prepare color prints with Printon, following the directions of the manufacturer and controlling each step of the process carefully. It was found that yellow, orange, and red colors could be reproduced with some degree of accuracy, as compared by the eye with the original subject. However, considerable variation in the reproduction of green colors was encountered. In order to study the reproduction of green colors more carefully, transparencies made of green color plaques were used for the preparation of color prints. This experiment failed because the glossy surface of the color plaques made it almost impossible to secure transparencies having an even distribution of light. A series of transparencies was then prepared from the color perception charts used to test for color blindness. It was thought that shift in color balance might be more readily detected in transparencies and prints made of these charts because of the apparent appearance, to a person with normal vision, of a number in the chart and apparent nonappearance to a person with color-blind vision.

The results from the preparation of the transparencies and color prints of these color perception charts were most interesting. In practically every transparency, the color chart appeared as seen originally, but none of the prints showed any color resemblance to the original chart. The appearance or nonappearance of the figures in the chart seemed to bear no relationship to the color balance in the print; for this reason, the transparencies and prints of the color perception charts were of no value in the exact determination of color balance, but some general observations could be made. The most important of these was that the

brilliance of the colors in the original charts was completely lost in the prints. In conferences early in the year with the Ansco laboratory personnel, it had been indicated that such loss would occur; however, this was the first instance where prints of definitely bright colors had been made at the Engineering Experiment Station. Re-examination of certain other prints showed that this loss in brilliance could possibly account for the failure of Printon to properly reproduce the colors of many objects. Another observation of value made on the prints of the color perception charts was that it was not possible in this laboratory to achieve a color balance of greens and reds in the same print. Whatever changes were made in compensating filters to correct the greens damaged the appearance of the reds, and vice versa.

All these examinations for color balance had been made in a most critical manner, and, because of the discouraging results, it was felt that possibly the process was being handled improperly. In order to make a comparison with commercial color prints, certain color transparencies of flowers and scenes made by personnel of the project with outdoor Ansco film were used for the preparation of color prints. It was found possible to produce prints of these subjects which compared very favorably with commercial work, and it was concluded that the basic principles of the process were being applied correctly.

At this time it was suggested that the project should prepare an exhibit for the "Trail Blazers Exhibit" of the National Chemical Exposition in Chicago. Because of the current interest in color prints, it was thought worthwhile to attempt to prepare a series of color prints

reproducing as nearly as possible the original colors of the foods, and to record the difficulties encountered in accomplishing this. As the green colors were most difficult to handle, it was decided to attempt to make prints showing the color changes in green beans and lima beans due to processing. Because it had been found impossible to secure the proper color balance of both greens and reds simultaneously, it was decided to make transparencies of piles of beans in such a manner that the camera field would be entirely covered with beans only.

Twelve transparencies were made, showing green beans or lima beans in the following conditions: (1) raw, (2) blanched, (3) immediately after quick freezing, (4) immediately after slow freezing, (5) quick-frozen, and (6) slow-frozen after 18 months storage. All these transparencies were made of 1/8 second, 2.4 light intensity on the Weston meter. The size of the beans in these transparencies was such that enlargement to 5 in. x 7 in. made them appear approximately life size.

The proper filters for the Printon emulsion were determined by using the standard transparency furnished by Ansco, and optimum exposure time for the prints was determined with the Haynes J-3 photometer. Despite all of this preliminary work, it was necessary to make 45 color prints before 12 were obtained which pictured the original color of the original objects. Furthermore, although all transparencies were made in the same manner, it was found that the exposure time and compensating filters necessary to produce a good color print varied from transparency to transparency. These data are shown in Table XII in order to illustrate the variations encountered.

TABLE XII

EXPOSURE TIMES AND COMPENSATING FILTERS NECESSARY FOR THE PRODUCTION OF ACCEPTABLE COLOR PRINTS FROM TRANSPARENCIES PREPARED BY AN IDENTICAL METHOD

Original Subject	Filters Required	Exposure Time Required, Seconds
Green Beans		
Raw	26, 35, 33	11
Blanched	26, 25, 35, 33	20
Immediately after Quick Freezing	26, 25, 35, 33	25
Immediately after Slow Freezing	26, 25, 35, 33	22
Quick-Frozen after 18 Months Storage	26, 35, 33	14
Slow-Frozen after 18 Months Storage	26, 35, 33	20
Lima Beans		
Raw	26, 25, 35, 33	20
Blanched	26, 25, 35, 33	21
Immediately after Quick Freezing	26, 25, 35, 33	32
Immediately after Slow Freezing	26, 24, 35, 33	18
Quick-Frozen after 18 Months Storage	26, 24, 35, 33	30
Slow-Frozen after 18 Months Storage	26, 24, 35, 33	20

Although only three combinations of filters were used in this series, there is a large variation in the times required for the production of an

acceptable print, and exposure time has a considerable effect on the resultant color balance.

In order to include in this report some examples of the color prints used for this exhibit, small prints were prepared from the center area of each larger print. After enlarging the image of the transparency on the easel to a 5 in. x 7 in., an area 2 in. x 3 in. was printed on Printon. In this manner nine copies were made. Here again some difficulties were encountered. Despite the use of a constant voltage transformer for the enlarger light, and a reliable electric timer, the resulting nine prints were not identical in color. A set of these small prints is included in this report as Appendix B.

As a result of the experimental preparation of color prints from Printon, it was concluded that the use of this material in the Georgia Tech laboratory for the exact reproduction of colors of foods is not feasible and that work on this method of recording the color of foods will be discontinued.

E. Leakage Determinations on Peaches.

1. The Effect of the Condition of Peaches Prior to Freezing on Leakage.

An unseasonal frost in the Spring of 1948 caused heavy damage to the peach crop in Georgia, and it was therefore difficult to obtain peaches of the exact maturity and freshness desired for the determination of the effect of the condition of peaches prior to freezing on leakage. However, several lots of suitable peaches were secured, and observations were made on these.

When the peaches were brought into the laboratory, they were examined carefully, and the bruised or rotten fruit was rejected. The peaches to be frozen were divided at random into groups of five each, quickly peeled, and sliced by three workers. The slices were then collected and mixed, and two workers immediately began to weigh out 50-gram samples into either cellophane bags or wire baskets. The samples in the wire baskets were immediately frozen in the immersion freezer in rapidly agitated alcohol at -20° F. for the three minutes required to bring the temperature of peach slices down to 0° F. These samples were then centrifuged in the immersion freezer for one minute to remove adherent alcohol, immediately sealed in cellophane bags, and stored in the 0° F. room in cardboard locker cartons. The samples which were weighed directly into cellophane bags were quickly sealed and stored in the 0° F. room in cardboard locker cartons. In this manner, a sample of five peaches was peeled, sliced, weighed, and removed to the proper conditions for freezing within less than ten minutes, thus minimizing the errors which might be caused by slices leaking fluid prior to freezing. Several samples of fresh peach slices were placed in mineral spirits and left for one, two, three and four hours and then weighed after wiping. The weight loss of those samples left one and two hours was negligible; after three hours it was one per cent; after four hours it was five per cent. Since the peach slices were prepared for freezing in less than ten minutes, it was felt that there was no error due to leakage prior to freezing.

As many samples as possible out of each lot of peaches were frozen and stored at $0^{\circ} \pm 0.5^{\circ}$ F. by immersion or in air, so that the effect of the condition of the peaches prior to freezing quickly or slowly could be

studied. About 1500 50-gram samples of peach slices were frozen and stored for these studies. The results of the studies made thus far are shown in Table XIII.

The values for leakage shown in Table XIII illustrate the difficulties encountered in obtaining consistent results from the examination of agricultural products. However, these results do show the great importance of the condition of the peaches prior to freezing in determining the quality of the frozen and thawed product. They also indicate an answer to why conflicting data have been obtained on the effect of various methods of freezing. Examination of the data in Table XIII for Lot No. 4 shows that there was no difference in the amount of leakage from the quick-frozen slices and that from the slow-frozen slices. The peaches from which these samples were prepared were small and hard. They had been shipped by truck from Kentucky and obviously had been picked green, and little or no ripening had taken place since picking. On the other hand, there was a consistent difference between the leakage values obtained from slow-frozen slices and from quick-frozen slices for all samples prepared from riper fruit which was frozen within at least 24 hours after picking. As the storage time prior to freezing increased, the difference between the leakage values obtained from slow-frozen and from quick-frozen slices decreased. Although these data are too few to be conclusive, they do suggest that the more succulent a fruit is, the greater will be the difference between the quick-frozen and the slow-frozen product.

The data in Table XIII seem to indicate that peaches lose moisture very rapidly when stored at 40° F., as indicated by the steadily decreas-

TABLE XIII

LEAKAGE* VALUES OBTAINED FROM PEACH SLICES
FROZEN IN VARIOUS CONDITIONS OF MATURITY AND OF FRESHNESS

Condition of Peaches (Elbertas) Prior to Freezing	Lot No.	Leakage, Grams per 100 Grams of Peaches	
		Frozen in Air**	Frozen by Immersion***
Tree Ripened, Fresh	1	38.5 ± 3.3	22.2 ± 2.8
Tree Ripened, Stored 24 Hours at:			
75° F.	1	46.2 ± 6.2	23.1 ± 1.2
40° F.	1	30.8 ± 1.5	17.2 ± 1.6
Tree Ripened, Stored 48 Hours at:			
75° F.	1	25.7 ± 4.0	19.1 ± 3.5
40° F.	1	24.0 ± 2.2	16.5 ± 3.5
Tree Ripened, 24 Hours in Transit	2	35.9 ± 0.5(1)	18.8 ± 2.0(1)
	3	36.6 ± 2.0(2)	27.0 ± 3.0(2)
Picked Green, 36 Hours in Transit	4	19.4 ± 3.2(2)	19.0 ± 3.0(1)
"Packing Ripe," 24 Hours in Transit	5	15.0 ± 4.5(1)	10.5 ± 1.0(1)
	6	23.6 ± 5.6(1)	14.6 ± 2.0(1)
"Packing Ripe," 24 Hours in Transit Stored 24 Hours at 75° F.	5	9.5 ± 1.5(1)	7.3 ± 1.0(1)
	6	16.6 ± 3.2(1)	10.1 ± 1.1(1)
"Packing Ripe," 24 Hours in Transit Stored 48 Hours at 75° F.	5	16.4 ± 3.3(2)	14.8 ± 2.0(2)

*Leakage was determined by removing preweighed 50-gram samples from 0° F. storage, placing in mineral spirits for four hours, wiping off mineral spirits, and weighing. The weight loss based on 100 grams of sample was reported as leakage. All values are an average for three determinations unless otherwise specified.

**Peach slices frozen in packages in 0° F. room. About six hours was required for freezing.

***50-gram samples of peach slices immersed in rapidly agitated alcohol at -20° F. for three minutes--the time required to bring the temperature of the peach slices to 0° F.

(1)Average of five determinations.

(2)Average of ten determinations.

ing leakage values obtained on peaches which had been stored at this temperature prior to freezing. On the other hand, peaches from this same lot, stored at 75° F., apparently became more succulent after 24 hours storage, prior to freezing, and then began to dry out between 24 hours and 48 hours of storage at this temperature. In general, the leakage values obtained from the peach slices frozen by immersion showed less change due to the condition of the peaches prior to freezing than did those obtained from peach slices frozen in air.

On the basis of the data shown in Table XIII, it would seem reasonable to draw the following conclusions:

(a) The maturity and freshness of peaches prior to freezing has an important effect on the amount of leakage obtained from slices of such peaches following freezing.

(b) In general, it appears that the less mature and the less fresh the peach is prior to freezing, the less difference there is between the leakage obtained from slow-frozen and that obtained from quick-frozen peach slices.

(c) The effect of the condition of peaches prior to freezing causes greater changes in the leakage values obtained from slow-frozen samples than from quick-frozen samples; therefore, slow freezing seems to be the better method for estimating the possible effect of prior condition on the quality of the frozen product.

2. The Effect of the Temperature to which Peach Slices are Cooled on Leakage.

In the early stages of the work on food freezing at Georgia Tech, it had been decided that the term "frozen" would be taken to mean that the various food products would be brought to a temperature of 0° F., because of the common acceptance of that temperature for the storage of frozen foods. However, it has been considered possible that the temperature to which a food is frozen might have some effect on the quality of the frozen product. Although it was not possible to investigate this phase of the work completely, preliminary experiments were carried out in which samples of peach slices were brought to temperatures of +20° F., 0° F., -20° F., either rapidly (within five to ten minutes) or slowly (about six hours), and leakage determinations run on these samples. The samples frozen rapidly were cooled in alcohol baths maintained at the temperature to which it was desired to cool the peach slices. The samples frozen slowly were placed in packages in still air of the temperature to which it was desired to cool the peach slices. The results of these experiments are shown in Table XIV.

The leakage values in Table XIV for peach samples cooled to various temperatures show certain inconsistencies. Thus, the samples cooled rapidly to +20° F. and stored at 0° F. (representing rapid cooling through "zone of crystallization," and slow cooling down to 0° F.) gave leakage results which were contradictory. The leakage results which were obtained from slices of fresh tree-ripened peaches were comparable with those obtained from slices of the same peaches which had been cooled rapidly to 0° F., indicating that the important factor in rapid freezing is rapid cooling through the zone of crystallization. On the other hand,

TABLE XIV

LEAKAGE VALUES* OBTAINED FROM PEACHES COOLED TO VARIOUS TEMPERATURES

Relative Rate of Freezing	Temperature to Which Frozen, °F.	Temperature at Which Stored for One Week, °F.	Leakage, Grams per 100 Grams of Peaches		
			Fresh, Tree-Ripened Peaches**	Peaches Picked for Packing, Allowed to Ripen Two Days***	Tree-Ripened Peaches, 24 hours in Transit****
Slow*****	0	0	38.5 ± 3.3	16.4 ± 3.3	36.2 ± 2.0
Rapid#	-20	0	18.4 ± 0.6		
Rapid	0	0	22.2 ± 2.8	14.8 ± 2.0	27.0 ± 3.0
Rapid	+20	not stored	15.4 ± 1.2	15.0 ± 3.8	
Rapid	+20	0	22.2 ± 1.6	15.4 ± 3.2	35.0 ± 5.0
Rapid	+20	+20			26.5 ± 2.0
Slow	+20	+20			28.0 ± 5.6

*Leakage was determined by placing the preweighed 50-gram samples in mineral spirits at 68° F. for four hours, wiping off the mineral spirits, and weighing.
**Averages of three determinations. Samples from Lot No. 1, Table XII.
***Averages of seven determinations. Samples from Lot No. 5, Table XII.
****Averages of nine determinations. Samples from Lot No. 3, Table XII.
*****Temperature of sample lowered to desired point within about six hours.
#Temperature of sample lowered to desired point within five to ten minutes.

the results obtained from slices of tree ripened peaches which had been 24 hours in transit were comparable with those obtained on the same peaches when cooled slowly to 0° F., indicating that it is equally important to cool samples rapidly down to the final temperature of 0° F. The results obtained from slices of the peaches picked for packing and ripened two days were of no value at all in this experiment, although they did confirm the observation made, based on the data in Table XIII, that the more immature and the less fresh the peaches are prior to freezing, the less difference there is between the leakage results obtained from samples frozen by different methods.

Another apparently contradictory set of results is seen in Table XIV when the leakage value for tree-ripened peaches which were 24 hours in transit are examined. The lowest value in this column in Table XIV is that obtained on peach slices cooled slowly to +20° F., and stored at +20° F. for one week. As this value is significantly lower than that obtained from slices cooled rapidly to +20° F. and stored for one week at +20° F., it is impossible, at present, to present any explanation of this apparent contradiction.

Because of the important effect of the condition of peaches prior to freezing on the leakage results obtained, it is essential that future work on the effect of the temperature to which samples are cooled be carried out on slices from peaches all of which are in identical condition prior to freezing. The results shown in Table XIV serve to confirm this observation, and are not of much value in ascertaining the effect of the temperature to which peach slices are cooled, or of the method by which they are cooled, on the leakage obtained from such

peach slices.

3. The Effect of Variation of Storage Temperature on Leakage.

In order to determine the effect of variation in storage temperature on leakage, five samples each of quick-frozen and slow-frozen peach slices from Lot No. 5 (Table XIII) were removed from 0° F. storage (where they had been held two months) and placed at 35° F. for 12 hours. It was estimated that this condition would permit the temperature of the peach slices to approach 28° F. without appreciable thawing, the initial freezing point of peaches being 28.5° F. These samples were then returned to 0° F. storage for 24 hours, and then removed for the determination of leakage. At the same time samples from the same lot which had been held in 0° ± 0.5° F. storage for two months were also examined for leakage. The results of this experiment are shown in Table XV along with the leakage results obtained from peach slices from this lot run immediately after freezing.

When the leakage values in Table XV for the results immediately after freezing are compared against the results after the two storage conditions, it can be seen that no significant difference in leakage was caused by the two months storage at 0° ± 0.5° F., but that a significant difference was caused by allowing the temperature of the samples to rise to 28° F. On the other hand, there is not a significant difference between the values obtained from the peach slices stored under the two different conditions.

The data in Table XV can be compared to those shown on page 236 of Annual Report No. 3 where the results of leakage determinations (by volume) on thawed and refrozen peaches showed a significant change in

TABLE XV

LEAKAGE* VALUES FOR PEACH SLICES FROM LOT NO. 5 FOLLOWING STORAGE UNDER VARIOUS CONDITIONS

Method of Freezing	Leakage, Grams per 100 Grams of Peaches		
	Immediately after Freezing**	After Two-Month Storage at 0° ± 0.5° F.***	Stored Two Months at 0° ± 0.5° F., Temperature then Brought to 28° F. and back to 0° F.**
In Air****	23.6 ± 5.6	26.4 ± 4.8	30.1 ± 7.0
By Immersion*****	14.6 ± 2.0	17.0 ± 4.8	19.0 ± 1.0

*Leakage was determined by placing sample in mineral spirits at 68° F.
**Average of five determinations.
***Average of 15 determinations.
****Peach slices frozen in packages in 0° F. room. About six hours was required for freezing.
*****50-gram samples of peach slices immersed in rapidly agitated alcohol at -20° F. for three minutes - the time required to bring the temperature of the peach slices to 0° F.

leakage to be caused by this thawing and refreezing. It must also be remembered that the penetrometer examinations on thawed and refrozen beans shown in Table VI of the present report indicate that the changes caused by thawing and refreezing are increased by storage following thawing and refreezing. For this reason, it will be necessary to obtain data after six months storage of peach slices following temperature fluctuations in order to evaluate properly the effect of these fluctuations.

In order to estimate the possible effect of small repeated variations in storage temperature on leakage, 15 samples from Lot No. 5 (Table XIII) were removed from 0° F. storage to an 18° F. room for two hours, and then returned to 0° F. storage for 24 hours. At the end of this time, leakage was determined on five of the samples; the remaining ten samples were held in the 18° F. room for two hours, and returned to 0° F. storage for 24 hours. This process was repeated each day for three days. The leakage values obtained from this experiment are shown in Table XVI.

TABLE XVI

LEAKAGE* VALUES OBTAINED FROM PEACHES OF LOT NO. 5**
WHEN THE STORAGE TEMPERATURE WAS VARIED DAILY**

Method of Freezing	Leakage, Grams per 100 Grams			
	No Temperature Fluctuation	One Fluctuation	Two Fluctuations	Three Fluctuations
Air, Slow***	26.4 ± 4.8****	26.0 ± 5.0	21.0 ± 1.6	22.0 ± 2.6
Immersion,***** Rapid	17.0 ± 4.8****	22.0 ± 3.6	18.2 ± 6.4	18.0 ± 1.0

*Leakage was determined by placing 50-gram samples in mineral spirits for four hours at 68° F., wiping off mineral spirits, and weighing. Values are the average of five determinations unless otherwise specified.

**The temperature was varied by removing samples from 9° F. storage to 18° F. storage for two hours out of each 24 hours.

***Peach slices frozen in packages in 0° F. room. About six hours was required for freezing.

****Average of 15 determinations.

*****50-gram samples of peach slices immersed in rapidly agitated alcohol at -20° F. for three minutes--the time required to bring the temperature of the peach slices to 0° F.

The data in Table XVI show a large amount of random variation, with the leakage values on the rapid-frozen samples tending to remain the same, and those on the slow-frozen samples tending to decrease with an increase in the number of temperature fluctuations, although none of the values show significant differences.

III. FUTURE WORK

It is planned that the work for the next three months will be concerned with the further study of the characterization of the physical condition of green beans, especially by drying rate and punch tests; a study of the application of drying rate determinations to the estimation of leakage in peaches; and a study of the possibility of determining the color of foods by reflectance using a rotating disk holder for the food samples.

Respectfully submitted:

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Approved:

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APPENDICES

APPENDIX A.

THE DETERMINATION OF THERMAL DIFFUSIVITY COEFFICIENTS OF VEGETABLES

By

C. G. JOHNSON AND F. J. STEVENS

A. Summary

This study was undertaken in order to determine the thermal diffusivity coefficient for a few selected vegetables in the temperature range of room temperature to 180° F. It was initiated due to the need for more complete and accurate information about the blanching characteristics of produce. Blanching is defined as a process whereby the produce sample is brought to a temperature sufficiently high (180° F.)[7] to cause the inactivation of those enzymes which are ordinarily associated with the deterioration of the sample during storage.

After an exhaustive literature search it was found that a cylindrical sample would be the most applicable solution to the question at hand. The samples were prepared in such a manner that the ratio of length to diameter was sufficiently large (five to one) so that the equations for cylinders of L = oo were applicable.[7]

In this problem the vegetables studied were string beans and Irish potatoes. The samples were blanched under three different sets of conditions: immersed in boiling water, suspended in a closed steam bath, and resting on a metal mesh tray suspended in a closed steam bath. The thermal sensitive elements used in measuring the temperature change during the blanching period were chromel-alumel thermocouples. The equipment used to register this information consisted of a General Electric Self-Balancing Potentiometer, equipped with a variable resistor, in conjunction with an Esterline-Angus milliammeter recorder.

The string bean sections were prepared by cutting appropriate lengths from the central portion of the beans as received, whereas the

potato sections were cut from the potato with a cork borer of 0.650 inch diameter. The thermocouples were then inserted into each sample in such a manner that the couple itself was positioned in the exact center. The string bean sections were next suspended in air, at room temperature, and allowed to equilibrate, while the potato sections were suspended above a water bath, slightly warmer than room temperature, and allowed to come to equilibrium. When the section had remained at a constant temperature for a period of three minutes, it was quickly immersed in the heating medium and the various temperature changes recorded.

From the data gathered, the value of the thermal diffusivity coefficient was calculated for each determination using the graphical method of Gurney and Lurie.[2] The most obvious and important conclusion that can be drawn from these results is that the values obtained for string beans and potato flesh were found to be very similar to those found for water in the same temperature range.[1] These results are substantiated by the high water content found in produce of this type.[5]

B. Object

To determine the thermal diffusivity coefficient for a few selected vegetables in the temperature range of room temperature to 180° F., so that heat transmission data can be calculated for this range.

C. Equipment

The high-speed temperature recorder used in this work has been described in Annual Report No. 3 (1948, pp. 68-79). The thermal sensitive elements used for this work were chosen because of their proven suitability in the temperature range of room temperature to 180° F.[3] The ther-

mocouples were prepared by spot welding No. 30 chromel and alumel wires so that the junction was no larger than the diameter of the wire itself.

The closed steam bath used in these determinations was in actuality a single-tray commercial type steam blancher. This steam blancher is presently in use at the Georgia Tech Research Station in conjunction with the project on the preservation of foods especially by freezing.

D. Procedure

The recorder was calibrated to read from 32° F. to 212° F. using 0.93 of full scale. The calibration was carried out using the boiling and freezing points of water and naphthalene and other thermal emf's commonly available.[3] The variable resistor allows the use of full scale for a wide range of thermal differences.

Due to the relative complexity and the fact that the equipment was still an experimental set-up, numerous difficulties were encountered in the actual use of the equipment. One of the most time-consuming difficulties was the necessity of rechecking the calibration prior to each run. Another was that the sensitivity of the potentiometer, while ordinarily an asset, was found to be somewhat of a hinderance due to certain unavoidable vibrations which existed during the working hours. This was overcome to some extent by the use of a finely balanced base resting on a series of coil springs and also by separating the instrument from the base with small pads of sponge rubber. Still another problem was presented by the presence, in the immediate vicinity, of several large automatic motors which tended to cause surges in the line voltage when cutting on. This difficulty was overcome by the insertion of a constant voltage trans-

former into the electrical circuit prior to the amplifier.

Although the use of the spring mount overcame most of the vibration of the amplifier, it caused difficulty in proper leveling of the instrument. By experiment it was found that a shift of 2° of the amplifier from the horizontal caused an approximate deviation of 3° F. from the correct temperature reading. To eliminate this error a light weight level was kept on the amplifier at all times.

In addition to the difficulties mentioned in the above paragraphs, many other time-consuming problems were encountered. Among these were the need for constant attention to be paid to the ice-water ratio for the reference junction and the necessity for preparing new thermocouples for each work period. Due to the size and inherent weakness of the thermocouple wire adjacent to the spot weld, there was frequent breakage of the junction even with the most careful handling.

Even though these difficulties just enumerated were not found to be insurmountable, they were found to be, indeed, very time-consuming. Over a period of weeks they were found to constitute, at a minimum, 50 per cent of the working time spent on the problem.

The string bean samples were prepared by cutting three-inch sections from the central portion of the freshest variety of bean to be found on the local market. The average diameter of these beans was determined by the use of a micrometer. Several different methods were tried and discarded for the proper positioning of the thermocouple within the bean. The method finally used consisted of piercing the bean through its center in the longitudinal direction with the thermocouple lead itself. Then by

careful measurement of the thermocouple one of the leads was bent at a distance from the couple equivalent to one-half the length of the section, and pulled into place. The sample was then suspended in the air and allowed to equilibrate to room temperature. The temperature was then allowed to remain constant for a period of about three minutes to assure stabilization, and the sample was quickly immersed in the heating medium.

The problem of correctly preparing the potato samples was found to be of a more difficult nature. After several unsuccessful attempts, the problem was finally solved in the following manner: In preparing the samples a cylindrical section of potato was obtained by using a large size cork borer (0.650-inch diameter). A cylindrical plug was then cut out through the center of this cylinder using a small cork borer, leaving a hole 0.200-inch in diameter. Then a potato plug slightly larger and longer was cut from the original potato. This small difference in size of the plugs was sufficient to compress the plug slightly, when inserted into the prepared cylinder, so that it fitted tightly without danger of slipping. This plug was then slit longitudinally, with a knife, half way through, and the thermocouple inserted lengthwise into the slit. One end of the thermocouple leads had been previously bent at a distance from the couple equivalent to one-half the length of the prepared cylinder so that when the plug assembly was inserted into the hole in the potato cylinder, the thermocouple itself would be located at the exact center of the cylinder. The excess length of the plug protruding out of the cylinder was trimmed off flush with the end of the cylinder, and the thermocouple leads were connected to the recording device. The sample was then suspended over water for about three minutes in a large beaker at

a temperature slightly warmer than room temperature and allowed to equilibrate. This was done to prevent the evaporation of moisture from the surface of the sample, thereby lowering the temperature.

The recorder was activated at the time the thermocouple was firmly placed within the section, and the time was marked when it was immersed into the heating medium. The Esterline-Angus recorder is so constructed that it traces a curve of emf change versus time. As the temperature of the center of the section rose, this change was plotted on the recorder paper and when the temperature reached the point in question the thermocouple circuit was then shorted out and the section removed from the bath. As a check on the accuracy of positioning the thermocouple in the exact center of the section, it was cut open and examined before removing the thermocouple. The data from those runs in which the thermocouple was poorly positioned were discarded.

E. Data and Calculations

During the time spent on this problem there were completed a total of 50 runs on string beans and potato flesh, of which 36 were found to be of an acceptable nature. The compilation of these data will be found in Tables XVII and XVIII.

The method of evaluating the results obtained in these determinations are taken from Chapter II of Heat Transmission by W. H. McAdams.[4] From this work there were found to be four basic equations of heat transfer in the unsteady state which are applicable to the work at hand:

TABLE XVII

DATA FOR THE DETERMINATION OF THE APPARENT AVERAGE THERMAL DIFFUSIVITY OF STRING BEANS FOR THE TEMPERATURE RANGE ROOM TEMPERATURE TO 180° F.

Run Number	t_b (°F)	Y	m	X	r^2 $(ft^2)(10^4)$	θ (hours)(10^2)	α' $(ft^2/hr)(10^3)$
1*	88.2	0.258	0	0.318	2.12	0.92	7.37
	87.0	0.256	0	0.320	2.91	1.00	9.35
	86.6	0.255	0	0.320	2.25	0.92	7.85
	88.2	0.258	0	0.318	2.25	0.94	7.58
	89.4	0.261	0	0.314	2.72	1.25	6.84
	88.2	0.258	0	0.318	1.67	0.82	6.47
	Average						7.58 ± 1.01
2**	88.2	0.258	0	0.318	2.46	0.78	9.75
	89.2	0.260	0	0.315	2.64	0.97	8.55
	89.7	0.261	0	0.314	2.33	0.92	7.96
	78.5	0.240	0	0.330	2.01	0.72	9.17
	79.5	0.241	0	0.330	1.84	0.86	7.05
	Average						8.50 ± 1.05
3***	79.5	0.242	0.17	0.435	1.84	1.07	7.48
	81.5	0.245	0.17	0.434	1.89	1.20	6.82
	81.5	0.245	0.17	0.434	3.23	1.74	8.05
	79.6	0.239	0.17	0.437	3.78	1.45	8.39
	79.6	0.230	0.17	0.437	2.47	1.13	9.55
	81.5	0.246	0.17	0.434	2.91	1.71	7.40
	81.5	0.246	0.17	0.434	2.64	1.14	10.05
	85.4	0.253	0.17	0.420	2.13	1.35	6.63
	Average						8.04 ± 1.23

*Beans suspended in steam maintained at 212° F.
**Beans on metal mesh tray in steam maintained at 212° F.
***Beans suspended in boiling water maintained at 212° F.

TABLE XVIII

DATA FOR THE DETERMINATION OF THE AVERAGE THERMAL DIFFUSIVITY OF IRISH POTATO FLESH FOR THE TEMPERATURE RANGE ROOM TEMPERATURE TO 180° F.

Run Number	t_b (°F)	Y	m	X	r^2 $(ft^2)(10^4)$	θ (hours)(10^2)	α $(ft^2/hr)(10^3)$
1*	80.4	0.243	0	0.330	7.32	6.34	6.17
	84.3	0.251	0	0.320	7.32	4.75	6.75
	82.4	0.247	0	0.325	7.32	4.92	6.36
	82.0	0.246	0	0.325	7.32	4.00	5.72
	81.5	0.245	0	0.327	7.32	4.92	5.68
	Average						6.14 ± 0.45
2**	76.5	0.236	0.12	0.406	7.32	3.92	4.71
	74.7	0.233	0.12	0.411	7.32	3.48	6.34
	75.6	0.235	0.12	0.406	7.32	3.75	6.04
	77.0	0.237	0.12	0.404	7.32	4.17	7.42
	76.6	0.236	0.12	0.406	7.32	4.23	6.04
	Average						6.11 ± 0.97
3***	80.5	0.243	0	0.330	7.32	4.00	6.04
	80.0	0.242	0	0.330	7.32	3.75	6.44
	79.0	0.241	0	0.331	7.32	3.62	6.72
	74.0	0.232	0	0.338	7.32	4.34	5.72
	75.0	0.232	0	0.338	7.32	4.31	5.75
	Average						6.13 ± 0.44

*Potatoes suspended in steam maintained at 212° F.
**Potatoes on metal mesh tray in steam maintained at 212° F.
***Potatoes suspended in boiling water maintained at 212° F.

I. $$Y = \frac{t' - t}{t' - t_b}$$

II. a) $$X = \frac{k\,\theta}{\rho c_p r_m^2} = \alpha \frac{\theta_2}{r_m^2}$$

b) $$\alpha = \frac{k}{\rho c_p}$$

III. $$m = \frac{k}{h\, r_m}$$

IV. $$n = \frac{r}{r_m}$$

The nomenclature used in these equations is that employed by McAdams.[4]

Since all samples were prepared by positioning the thermocouple at the exact center, it follows that "n" for all runs was zero. From the literature search conducted prior to the actual beginning of work, information was found which led to the belief that "m" would be zero for the conditions to be used.[7] After the initial work was completed and the calculations begun, it was found that identical values of α were not obtained from the data for all conditions. It was therefore assumed that "m" was not zero for all the conditions used. Although "m" was assumed to be quite small for certain of these runs, it had a finite value and therefore affected the calculations. The value of "m" could normally be calculated from Equation III, but from the literature search no reliable values for "k" and "h" could be found.

Knowing that "h" for steam to the sample would ordinarily be of a high order,[3] it was assumed that the value of "m" for the runs where the samples were suspended in steam was zero. From the calculations made it was found that this held true for string beans but was not the case for potato flesh resting on the metal mesh tray. As all runs were made with sufficient sample length to give a ratio of length to diameter of

at least five to one, the value of "m" could be calculated from a chart of $L = \infty$.[4] From the chart the correct value of "m" for all runs where "m" was not zero could be calculated by knowing the correct value of α. As can be seen from Tables XVII and XVIII this correct value of α, with "m" = 0, was found from the runs where the sections were suspended in the closed steam bath. With this new, correct value of "m" the results of the runs where "m" was not equal to zero could be recalculated giving the corrected results. These values are also shown in Tables XVII and XVIII.

Actual values of t, t^1, t_b, θ, and r_m are available from the data gathered; hence Y can be calculated from Equation I. With this value of Y and the proper value for "m", a corresponding value of X can be read directly from the Gurney-Lurie graph shown by McAdams.[4] From this value of X, the value of α can be calculated directly from Equation II a. With approximate values of ρ and c_p, which can be obtained from the literature,[6] a first approximation of "k" can be made by use of Equation II b. As a check on the consistency of the results, the standard deviation was calculated by the root mean square method.

All the data compiled and calculated in this work are shown in Tables XVII and XVIII along with the average value of α and the standard deviation.

F. Conclusions and Discussion

When the problem was initiated, a search of the literature was made in order to determine the most appropriate method of attack. It was decided that a cylindrical shaped section would be the most desirous

for a number of reasons. The first and most important of these was the fact that a cylindrical section of L = oo has no temperature gradient in its longitudinal direction.[7] This would provide the most advantageous conditions for the accurate determination of temperature at the center of a sample. Another of these was the problem of availability of produce in this area. It was found that string beans, which are originally in this cylindrical shape, were the most abundant during the working period. The Irish potato, which is so easily shaped into any desired form due to its nature, was also chosen. Its availability the year around was an additional factor in the choice.

There were several factors influencing the choice of conditions for blanching the samples. The foremost of these was that the work was done for the purpose of gathering data concerning the conditions under which produce is blanched in commercial practice. The conditions chosen -- boiling water and suspension in steam -- were found to be the most commonly used commercial methods.

There was noted in the literature several statements commenting upon the characteristic physical properties found for vegetables containing a high water content.[1] These properties were found to be markedly similar to those found, independently, for water in the same temperature range. The present accepted theory holds that the percentage of water content in these vegetables is sufficient to control largely the value of these characteristic physical properties. The results obtained from our determinations were found, in general, to conform to this theory.

Upon examination of Tables XVII and XVIII, it can be seen that there is good agreement between the values of α found for string beans under

different conditions. These average values, however, had a rather large standard deviation, especially in comparison with those found for the potato runs. This difference can be largely explained by the variations in size, structure, and maturity found in the string beans as compared to potatoes. While the size of the string bean sample was at all times dependent upon the produce obtained, the potatoes could be cut to a standard size each time. There was also more room for variation in the string bean samples because of the greater difficulty encountered in positioning the thermocouple within the sections.

The similarity of the results found in this problem to those found for water can be easily demonstrated. The average value of α, for all conditions, was found to be 8.02×10^{-3} for string beans and 6.12×10^{-3} for potatoes, while Colburn[1] gives the value for water in this temperature range to be 6.10×10^{-3}. In view of the presently held theory, this greater similarity for potatoes than beans to water is explained and substantiated by its higher water content.[6]

It will be noted that a suggested method for calculating "k" and "h", for the work done, was developed, but that no values for these properties were listed in Tables XVII and XVIII. This was necessitated by the lack of reliable data to calculate these values. Exact values of ρ and c_p could not be found during the literature search, but approximate values[6] were used to make a first approximation of "k". By the use of Equation II b, "k" was calculated to be 0.457 BTU/(hr)(ft^2)($^\circ$F/ft) for string beans and 0.346 BTU/(hr)(ft^2)($^\circ$F/ft) for potato flesh in the temperature range, room temperature to 180° F. From Equation III, "h" could be calculated for the runs where "m" did not equal zero. But this value

of "h" would be, in any case, only as good as the value of "k". These values were not listed in Tables XVII and XVIII, but a first approximation can be made. For the case of string beans in boiling water, "h" was found to be 170 BTU/(hr)(ft^2)(^oF) and for potato flesh resting on a metal mesh tray in a steam bath, it was found to be 107 BTU/(hr)(ft^2)(^oF).

On the basis of the work done on this problem it is possible to calculate the time-temperature data necessary to successfully carry out a commercial blanching process. From the calculations made in this study there was found to be a small, but significant, difference existing between the conditions investigated. It can be concluded, from this, that these differences are not sufficiently large to be a controlling factor in the choice of a commercial blanching process.

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APPENDIX B.

COLOR PRINTS SHOWING COLOR CHANGES IN GREEN BEANS AND LIMA BEANS

A. Fresh

B. Blanched

C. Immersion-Frozen,
Immediately after Freezing

D. Air-Frozen,
Immediately after Freezing

E. Immersion-Frozen,
Following 18 Months
Storage at 0° F.

F. Air-Frozen,
Following 18 Months
Storage at 0° F.

Figure 4. Color Prints of Green Beans

A. Fresh

B. Blanched

C. Immersion-Frozen,
Immediately after Freezing

D. Air-Frozen,
Immediately after Freezing

E. Immersion-Frozen,
Following 18 Months
Storage at 0° F.

F. Air-Frozen,
Following 18 Months
Storage at 0° F.

Figure 5. Color Prints of Lima Beans

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PROGRESS REPORT NO. 20

PROJECT NO. 98

FOOD PRESERVATION

Prepared for

TENNESSEE VALLEY AUTHORITY

By

F. BELLINGER, T. W. KETHLEY, and W. B. COWN

OCTOBER 1, 1948-DECEMBER 31, 1948

GEORGIA INSTITUTE OF TECHNOLOGY
THE STATE ENGINEERING EXPERIMENT STATION
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Progress Report No. 20, Project No. 98

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Progress Report No. 20, Project No. 98

I. SUMMARY

During the period covered by this report, a method was developed by which the color of food products may be measured by reflectance using a spectrophotometer and rotating sample holder; a study of the application of the drying rate determination to the estimation of leakage in peaches using both the Dietert Drier and the Aminco Temperature Cabinet was initiated; the study of the determination of the drying rate of green beans was continued; and the examination of frozen food samples which had been stored at 0° F. for 12 months was made.

A thorough review and analysis of the results of previous studies of the measurement of color of food products by reflectance revealed that the greatest difficulty in obtaining reproducible data was that of proper sampling. A rotating sample holder was devised by which a representively large area of food product can be mechanically intergrated so that the "average" color and appearance of the surface of the sample can be measured. Initial experiments using color photography to record the color image of the rotating sample indicated that it was possible to record the average color of green beans when rotated on a disc at 370 rpm by means of color transparencies taken at 1/4-second exposure time at a Weston light intensity of 2.4. Since a sensitive and reliable instrument was needed for the measurement of the density of the resultant transparencies, the rotating disc was used in conjunction with the spectrophotometer so that the color measurement of foods could be made directly without the need for intermediate color transparencies. It was possible to obtain reproducible readings using the spectrophotometer as long as the speed of rotation was 100 rpm or greater. Measurements were made on raw, blanched, and frozen and thawed

green beans and carrots. The results were plotted to form spectral response curves which were analysed by Hardy's[1] ten-selected ordinate method, and the color specified in terms of chromaticity according to the method of color specification recommended by the International Commission on Illumination.

Some work was accomplished on the application of a drying rate determination to an estimation of leakage in peaches in hopes of correlating leakage values with drying rates, and, also, to eliminate the necessity of removing the excess fluid adhering to the surface of the peach slices prior to final weighing. Preliminary runs were made using the Dietert Drier but this method was discarded since the supply of warm air was inadequate to remove all the adhering surface fluid. The Aminco Temperature Cabinet was then converted to a drying chamber in which a comparatively large volume of warm air was available, and a sample holder capable of holding nine samples was constructed. Several runs were made using 50-gram samples of peach slices with various conditions of thawing prior to drying, and allowing various times of exposure in the air stream at 150° F. Although the work is incomplete, the initial results indicate that leakage values and drying rates may be correlated.

Further studies were made on the use of the drying rate determination in characterizing the physical condition of green beans employing the Aminco Temperature Cabinet in place of the Dietert Drier used previously. Several tests were carried out while varying the lapse of time between removal of sample from 0° F. storage and initiation of drying, as well as the time of drying, in order to determine the conditions of the test which would yield the most reproducible data and

also indicate differences in the condition of green beans, either due to the nature of the beans or to the processing employed. Preliminary tests indicated a difference between samples which were slow frozen and those which were rapid frozen, greater weight losses being obtained in the case of slow frozen samples. Though inconclusive due to the small number of determinations made, the most reproducible data were obtained by allowing four hours for thawing and then drying for 30 minutes in an air stream at 150° F.

The examination of frozen samples stored at 0° F. for 12 months was completed, but there was insufficient time during this work period to analyze the data obtained.

II. EXPERIMENTAL WORK

A. Measurement of the Color of Green Beans by Reflectance

1. Introduction

The previous work (Annual Report No. 2, 1946, pp. 119-135 and Annual Report No. 3, 1947, pp. 30-40) carried on in this laboratory on the measurement of the color of foods by reflectance yielded no results which were useful in characterizing changes in foods due to processing. This failure primarily was due to the fact that the measurements were made on single specimens of vegetables, and the variation from specimen to specimen was excessive. Following this initial work, which involved the use of the spectrophotometer and reflectance accessory, an extensive investigation was made of the possibility of preparing reproducible color prints for recording and disseminating information concerning color changes in foods. Although the transparencies obtained by color photography have been found satisfactory as a laboratory tool for reproducing and recording the colors of foods, it was not found possible to produce color prints which represent the true colors. Therefore, work on color prints was abandoned.

Since color is recognized by most workers in the food industry as characterizing the quality and acceptability of various food products, a thorough review and analysis was made of the results of previous studies on color measurement. It was concluded that the major difficulties presented were not merely those involved in accurately measuring and recording the color of a particular section of material, but were also those of obtaining results which would be representative of the sample in question. For example, slight variations in actual color and

shape may exist between two different spots on any one individual bean as well as between two beans of any one group. Generally, however, these differences in appearance are not as great as exist between two separate groups of beans when each group is observed as a whole. In order to overcome the problem of sampling, it has been suggested by some workers in the field that the product be pureed. This procedure yields a representative sample, but unfortunately the sample is not a measurement of the surface appearance of the food. It was concluded that some means of mechanically integrating a representatively large area of food product was needed so that the "average" color or appearance of the surface of the sample could be measured and recorded.

It was found in this laboratory that an estimate of the average color of a sample of green beans could be made if several beans were mounted on a circular holder and rotated rapidly. The underlying principle is that employed in mixing colors on a color disc, where several colors or shades of the same color are mounted on a disc which is then rotated rapidly enough for all of the color components to blend into a single color. This resultant color is the sum of all of the component colors on the disc. Furthermore, if the disc is rotated rapidly enough, any irregularities in the physical thickness, shape, and spatial arrangement of the colored materials are apparently averaged to a single uniform level and arrangement.

2. Description of the Rotating Disc and Reference Standard

A sample holder for the study of the color of green beans was fabricated from a circular needle flower holder. The needle flower holder was mounted on a spindle, and a pulley was attached to the spindle

so that the holder could be rotated by an electric motor. This assembly can be seen in Figure 6. The mounted needle flower holder, or rotating disc, employed was 3-1/2 inches in diameter and had a large number of needles projecting 1/2-inch above its base. The spindle was so arranged that the speed of rotation of the disc could be varied by the use of different size pulleys. Samples of produce, such as green beans, were mounted on the disc by impaling the individual items on the disc so that the surface of the disc was essentially covered. The disc was then rotated and studies made on the average color of that particular sample.

It was first necessary to determine the minimum rate of rotation required to cause blending of the colors of the individual beans and to cause an apparent leveling of the physical irregularities of the individual units of the food product. A series of color transparencies was made of a disc loaded with green beans rotating at 370 rpm and at 1140 rpm. The light intensity was 2.4 on the Weston meter and times of exposure of the films were 1/8-, 1/4-, and 1/2-second, respectively. Examination of these transparencies revealed that the films exposed for 1/8-second contained circular lines for both the 370 and 1140 rpm speeds, indicating that for any instrument which has the ability to "see" color changes in less than 1/8-second, a disc speed of rotation greater than 1140 rpm would be required. The films exposed for 1/4-second for both the 370 and 1140 rpm runs showed only slight streaking and those exposed for 1/2-second were uniform in appearance. In no instance was there any great difference between the results for a given time of exposure due to the difference in rate of rotation.

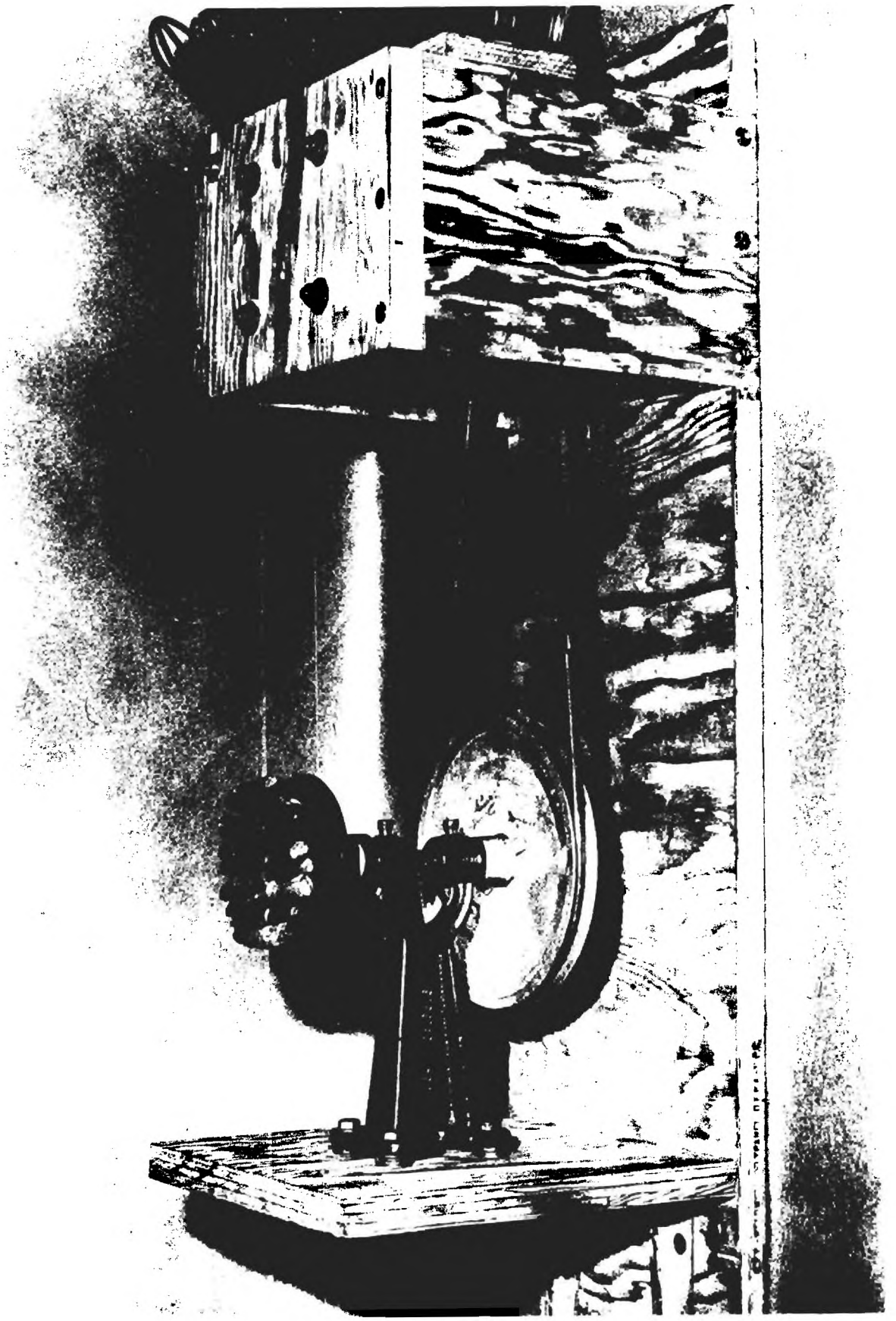


Figure 6. The Rotating Disc Assembly

In order to estimate the possible value of color transparencies for this work, the above experiment was repeated using (1) a sample of dark green beans and (2) two samples of light green beans from the same lot. Color transparencies were made at exposure times of 1/8-, 1/4-, and 1/2-second, respectively, the disc being rotated at 370 rpm. The light intensity for all exposures was 2.4 on the Weston meter. No exposures were made at 1140 rpm since there had been no appreciable differences in the first transparencies due to the change in the rate of rotation. The individual transparencies were inserted into an Omega DII enlarger equipped with a No. 212 bulb and color head. The image of the transparency was then focused on the field of a Haynes J-2 Photometer, and estimates made of the density of the transparency with the following filters in the color head of the enlarger: (1) no filter, (2) Ansco No. 25 yellow filter, (3) Ansco No. 35 magenta filter, and (4) Ansco No. 45 cyan filter. In this manner, the density of the color of the transparency in several ranges of visible light was estimated. Because the Haynes J-2 Photometer is a visual instrument, these measurements were not very accurate. However, this study showed a difference between the densities of the transparencies made of the light green beans and those made of the dark green beans, and a similarity between the transparencies made of the two samples of the light green beans. A shift in the relation of the color components was observed between the transparencies made at 1/2-second exposure and those made at 1/8- and 1/4-second exposure. This shift may be explained on the basis that the 1/2-second exposure time was too great to maintain the proper color balance at a Weston light intensity of 2.4. The Omega DII enlarger and Haynes J-2

Photometer are shown in Figure 7.

These initial experiments produced results which were very encouraging, indicating that it should be possible to record the average color of green beans, when they are rotated on a disc at 370 rpm, by means of color transparencies taken at 1/4-second exposure time at a Weston light intensity of 2.4, provided a sensitive and reliable instrument such as a spectrophotometer is used for the measurement of the density of the resultant transparencies.

Although the results of the original work on the measurement of color by reflectance had not been particularly encouraging, it was thought worthwhile to try to determine color of foods directly by using the rotating disc and a spectrophotometer with reflectance attachment. The use of a rotating sample holder with the spectrophotometer was suggested by Dr. J. W. Gabel, Calco Chemical Division, American Cyanamid Company, Bound Brook, New Jersey, and was based on the work of a co-worker, Dr. Robert H. Park, who had patented a similar device for use with the General Electric recording spectrophotometer. Dr. Park reported much success with measurements on sheet material and cloth. He found that by placing the axis of the rotating disc off-center with respect to the viewing aperture of the spectrophotometer, the total area of the sample viewed could be substantially increased beyond that possible by viewing an axial area of a rotating sample through an aperture of equal size. In fact, the greater the distance between the axis of rotation and the center of the scanning aperture, the greater the area of sample the instrument can "see" in a given rotation. Since this method would enable the use of a comparatively large sample with an irregular surface,

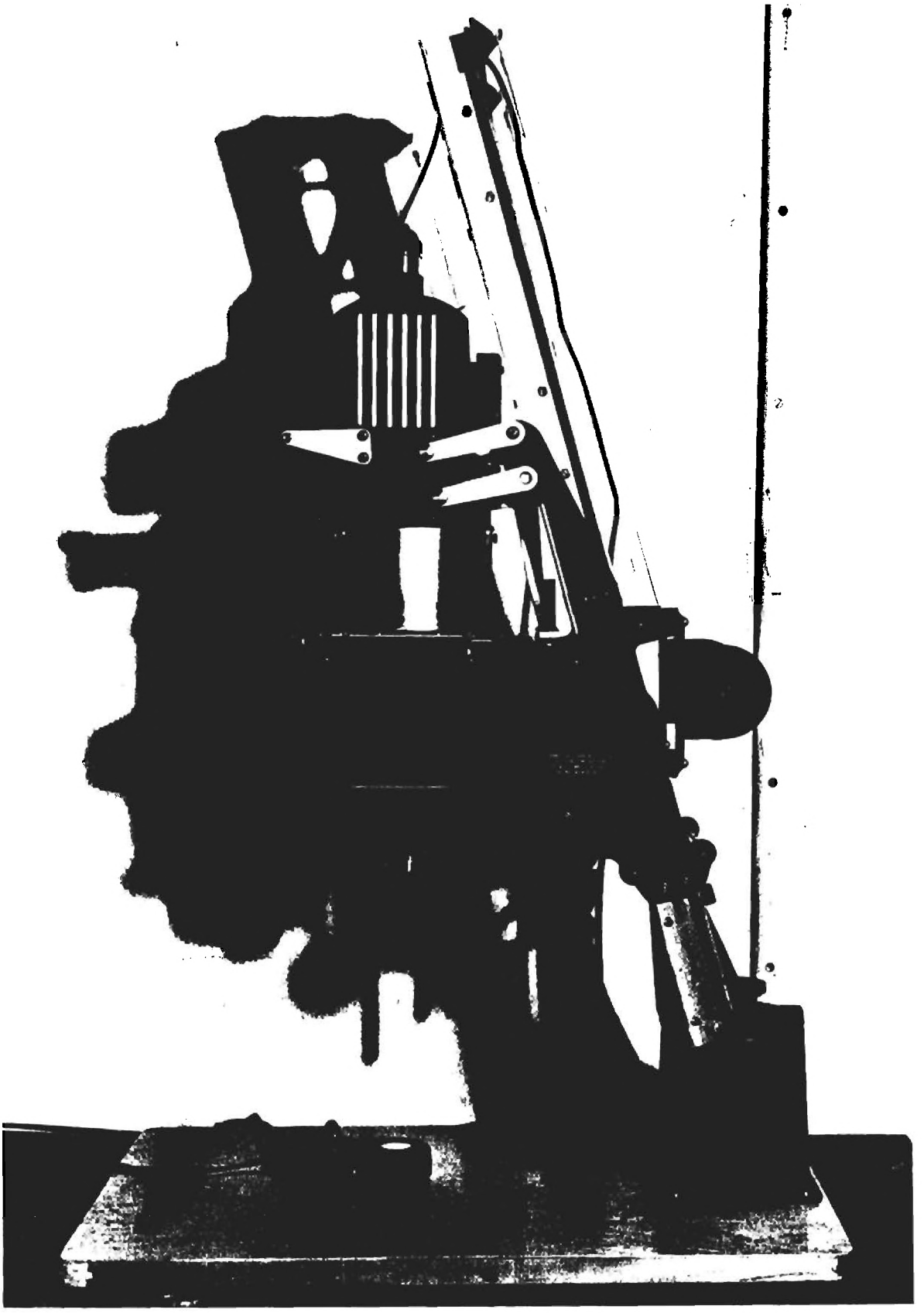


Figure 7. The DII Omega Enlarger and Haynes J-2 Photometer

the next group of experiments in this laboratory were concerned with the direct measurement of the color of green beans on a rotating disc, rather than of transparencies made of the green beans. The Beckman spectrophotometer, with reflectance attachment, was mounted on a platform of sufficient height to allow about 1/4-inch between the top of the needles of the rotating disc and the bottom of the reflectance unit. The rotating disc assembly was then positioned so that the center of the scanning aperture of the reflectance unit was located just above a point midway between the center and the periphery of the rotating disc. When positioned in this manner, the area viewed on the rotating disc is equal to the area of the viewing aperture extended along a closed path around the periphery of the disc surface. After the rotating disc assembly was properly located, the end of this assembly bearing the motor was placed at right angles to the spectrophotometer, and secured to the table by a pivot. A stop was provided so that the rotating disc assembly could be swung from under the reflectance unit for the mounting of a sample, and subsequently moved back into the proper position under the reflectance unit for studying the sample. The details of this equipment lay-out may be seen in Figure 8. No provision was made for a light-tight housing between the reflectance unit and the rotating disc. Hence, the examination of the samples was carried out in the dark, using a pin point light to read the instrument dials.

Normally, to operate the reflectance unit, a standard white magnesium carbonate block, freshly smoked with magnesium oxide (99+ per cent pure white) is placed in one compartment of the reflectance accessory drawer, and the sample to be measured in the other compartment. Read-

Figure 8. The Beckman DU Spectrophotometer with Reflectance Accessory and Rotating Disc Assembly

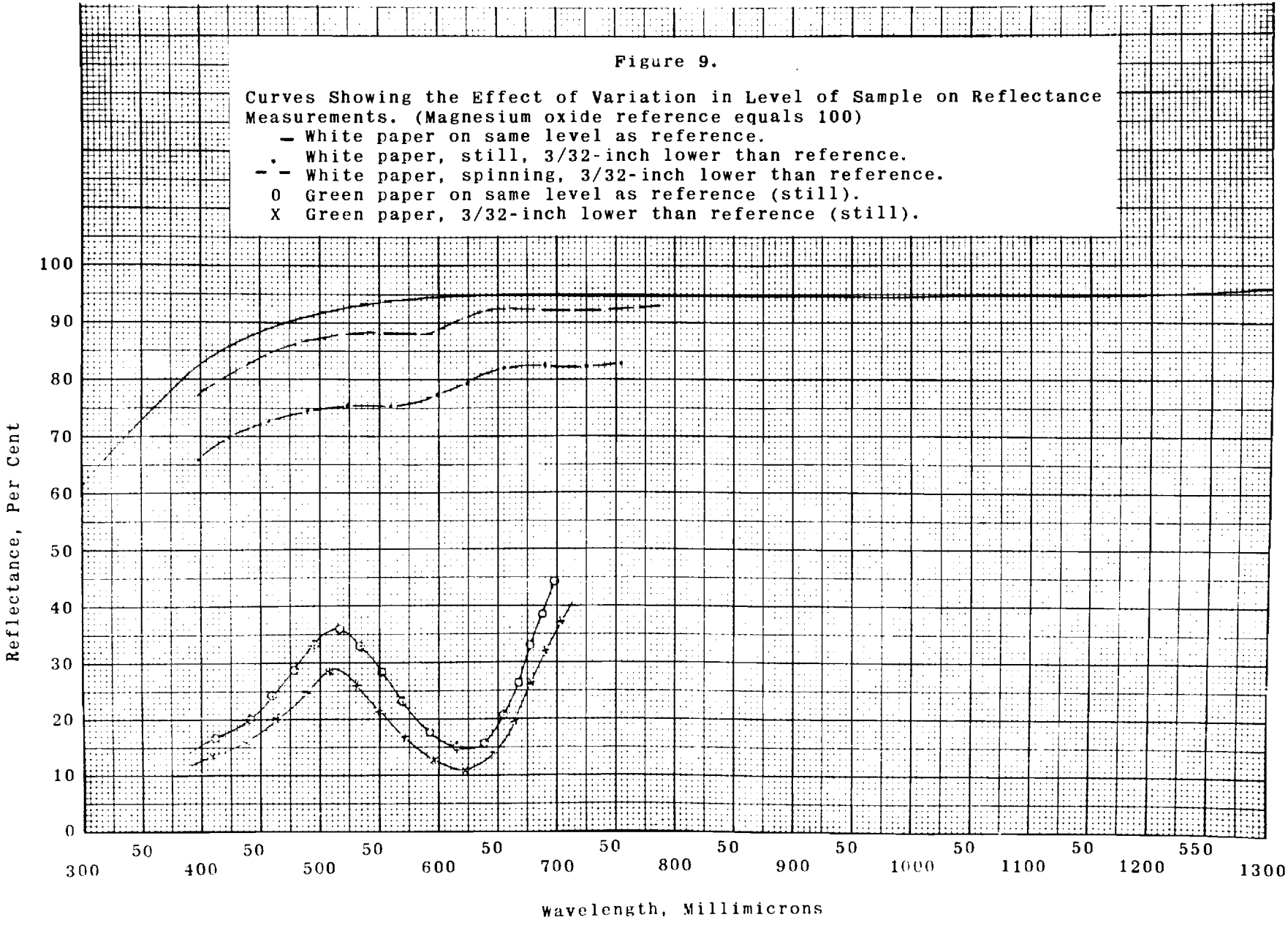
ings are then made at various wavelengths, setting the standard to 100 per cent reflectance for each wavelength studied, and then balancing the instrument on the sample and reading the per cent reflectance. In the drawer, the sample is positioned about 1/32-inch from the bottom of the reflectance unit and is held level at this point. When the instrument was set to 100 per cent reflectance for the standard smoked magnesium carbonate in the drawer, and then this same standard held 1/4-inch below the reflectance unit, the reading dropped to 88 per cent for most wavelengths, indicating a significant, but not excessive, light loss due to scattering. To determine the linearity of the light loss, a sample of red cloth was placed in the sample drawer and readings were made at several wavelengths; then the sample drawer containing both standard and sample was lowered 1/4-inch below the reflectance unit and the readings repeated (again setting the standard to 100 per cent for each wavelength considered). The same readings were obtained in both cases, indicating that the light loss is linear and that samples can be measured at levels lower than normal provided the standard is maintained at the same level as the sample. In order to determine the effect of tilting the sample, the standard smoked magnesium carbonate block was read as 100 per cent reflectance when level, and then tilted about 15° to the left, which resulted in a reading of 101 per cent being obtained. When tilted about 15° to the right, a reading of 103 per cent was obtained. These findings indicate that care must be taken to have the sample and standard parallel to the bottom of the reflectance unit, but that slight deviations from this will not cause particularly large errors in results.

Inasmuch as the fragility of the "standard" magnesium carbonate block was a source of trouble, it was considered desirable to obtain a more substantial standard. A satisfactory substitute was found in a white blotting mat used in drying photographic prints. Although this material is not as white as the carbonate block, it is sufficiently uniform in color and texture for investigational purposes. Being 1/32-inch in thickness, one sheet was thin enough to slide between the sample of beans and the reflectance unit, and not cause a perceptible error in measurements due to the difference in level between its surface and the surface of the sample of beans. On the other hand, one sheet was sufficiently thick to be opaque as evidenced by the fact that the same readings were obtained from a single thickness as were obtained from several thicknesses. It was therefore decided to use this material as the reference standard instead of the smoked magnesium carbonate block, and a detailed study of its reflectance relative to that of the smoked magnesium carbonate block was made. The results of this study are shown by the solid-line curve in Figure 9. In this same figure are shown curves for the readings made on the white paper when it was placed on top of a sample of beans (3/32-inch below the level of the reflectance unit), both when still and when spinning. Analysis of these curves reveals that the only significant difference among the three is in brightness, i.e., the relative location of the curve on the vertical axis. The same conclusion applies to the two curves shown in Figure 9 which were obtained from a sample of green paper. These findings indicate that the use of the white paper for a reference standard should give results equivalent to those obtained with the use

Figure 9.

Curves Showing the Effect of Variation in Level of Sample on Reflectance Measurements. (Magnesium oxide reference equals 100)

— White paper on same level as reference.
. White paper, still, 3/32-inch lower than reference.
– – White paper, spinning, 3/32-inch lower than reference.
0 Green paper on same level as reference (still).
X Green paper, 3/32-inch lower than reference (still).



of the smoked magnesium carbonate block, except for the brightness values, and that these can be corrected by the use of the proper correction factor.

Before proceeding with the measurement of the color of beans by reflectance, it was necessary to determine experimentally a speed of rotation which would be suitably related to the rate of response of the measuring instrument. The following experiments, which were performed to determine the proper rate of rotation, were based on the fact that the position of the spectrophotometer milliammeter, or balancing, needle varies with differences in color and surface of the sample and that there is some speed at which the sample can be rotated so that the milliammeter needle remains fixed, due to its inertia. A disc of blotting paper was placed on the rotating disc and colored uniformly with green ink, and then irregular darker streaks of green were made on the paper with the same ink. To simulate irregularity of surface, indented lines of about 1/16-inch depth were made across the surface of this paper (with a stylus). A variable speed motor was then used to rotate the disc at varying speeds and reflectance readings were made at the wavelength of 400 millimicrons. There was no perceptible variation in reading due to changing the speed of rotation of the disc, from 100-1700 rpm, the average reading being 7.5 per cent reflectance. However, when the disc was rotated at speeds below 100 rpm, there was a perceptible wavering of the needle of the balancing meter of the spectrophotometer, indicating that the rate of rotation was inadequate to level out differences in color and height. When the motor was turned off, and the disc rotated by hand, spot readings (made when the disc

was still) varied from 7-11 per cent. In order to check these observations with greater variations in color, streaks of red were added to the green ink on the disc so that individual spots gave readings varying from 2-15 per cent at 400 millimicrons. The disc was then rotated at speeds varying from 100-1700 rpm and no wavering of the needle of the balancing meter of the spectrophotometer was observed. A group of green beans was placed on the disc and 15 spot readings made at a wavelength of 540 millimicrons, with results ranging between 27.8 - 41.3 (arithmetic mean of 35.0) per cent reflectance. When the sample was rotated at 370 rpm the per cent reflectance was found to be 35.5. It was therefore concluded that rotating the disc in excess of 100 rpm would average large differences in color and surface within the sample. As the rotating disc had previously been set up to operate at 370 rpm while driven by a constant speed motor, this rate of rotation was considered acceptable and used in all subsequent measurements made with the rotating disc.

3. The Measurement of the Color of Green Beans by Reflectance on the Rotating Disc

The primary objective in making reflectance measurements on foods being to measure color as seen by the human eye, the first determinations were limited to the wavelengths of visible light--from 400-700 millimicrons. For these determinations, the Beckman spectrophotometer was set at 0.1 sensitivity and 0.1 mm. slit opening. Readings were made at intervals of 10 millimicrons in the range 400-500 millimicrons; 20 millimicrons in the range 500-600 millimicrons; 25 millimicrons in the range 600-700 millimicrons. For the slit width of 0.1 mm., the average band width for the range 400-500 millimicrons

was 2.0 millimicrons; for 500-600 millimicrons the average band width was 3.5 millimicrons; and for 600-700 millimicrons the average band width was 5.0 millimicrons. These band widths and intervals of reading were considered sufficiently small to assure the proper recognition of any maxima and minima that might be shown by the reflectance curves of green beans in the region of visible light.

The samples of green beans were prepared by impaling lengths of beans on the needles in such a manner that the surface of the disc was completely covered with beans insofar as was possible. After impaling the beans on the needles, the beans were leveled by pressing down uniformly on them with a flat board, taking care not to crush the surface of the beans. After the preparation of the sample, the rotating disc was swung into position beneath the base plate of the reflectance unit, and a section of white blotting mat 3- x 6- x 1/32-inch was placed on top of the sample. The room was then darkened to eliminate the stray light entering the clearance space between the rotating holder and the base plate of the reflectance attachment, and subsequent instrument readings were made with the aid of a pin point light. The spectrophotometer was first balanced to 100 per cent reflectance against the white paper reference standard. The paper was then removed from the top of the sample and the sample rotated at 370 rpm. The per cent reflectance for the particular wavelength was read and recorded. This procedure was repeated for the various desired wavelengths of light, and the data recorded in tabular form. These data show that the reproducibility of a given reading was of the order of $\pm$ 5 per cent. Curves, such as Figures 9 and 10, were then constructed.

As previously discussed (pp. 30-40, Annual Report No. 3, 1947), the analysis of reflectance data is complex and the choice of the proper method of analysis is often difficult. The reflectance data obtained for green beans in the present experiments were analyzed by the method of the International Commission on Illumination (I. C. I.) method of ten-selected ordinates for Illuminant C, representing daylight, as described by Hardy[1]. A discussion of the background theory and the method of analysis is presented in the Appendix of this report. The methods, tables, and chromaticity diagrams referred to in the Appendix, and in the present discussion, are those found in the Handbook of Colorimetry by Hardy. In brief, this method consists essentially of locating the per cent reflectance value for a given sample at ten selected wavelengths for each of three tristimulus (or primary color) values X, Y, and Z. To expedite the compilation of these values, vertical lines were drawn on sheets of thin linear coordinate paper through the selected wavelength points for each tristimulus function. To compile the data for the determination of a tristimulus value, the paper marked for the proper tristimulus function was superimposed on a sheet of paper having a reflectance curve drawn upon it; both sheets were then laid on the surface of an illuminated X-ray viewer. In this manner the data could be read quickly from the intersection of a vertical line with the reflectance curve. The tristimulus values X, Y, and Z were obtained by summing the values of the ten-selected ordinates for each, and multiplying by a factor. These values were then employed to obtain the tri-

[1] Hardy, A. C., Handbook of Colorimetry. The Technology Press, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1936.

chromatic coefficients x and y by means of the equations:

$$x = \frac{X}{X+Y+Z} \quad (1)$$

$$y = \frac{Y}{X+Y+Z} \quad (2)$$

The trichromatic coefficients are then employed to locate the dominant wavelength and purity of the color on chromaticity diagrams. The third attribute of a color, brightness, is given directly by the value Y.

In using a white reference standard which is not 100 per cent pure white, it can be seen from equations 1 and 2 that the values obtained for the trichromatic coefficients will not be affected, provided the white used as a reference has a fairly uniform reflectance value (compared to a 99+ per cent white) in the range of wavelengths of light under investigation. As can be seen from the solid line curve in Figure 9, this is not exactly true for the white paper used as the reference white in this work, as its reflectance varies from 83 per cent at 400 millimicrons to 95 per cent at 700 millimicrons; the greatest variation being in the range 400-500 millimicrons. This would affect the estimation of Z, the ordinates of which are located in this range. However, it was found that correcting for this variation gave values of Z which were only slightly (less than five per cent) different from those obtained without applying the correction, so that this slight error was disregarded for the analyses presented in this report. However, the value for brightness, Y, is directly affected by the impurity of the white reference, and must be corrected by multiplying the value obtained by 0.93. The value 0.93 is the average per cent reflectance, divided

by 100, of the white paper as compared to the smoked magnesium carbonate block for the wavelength range 490-625 millimicrons, the range from which the data for the determination of brightness are derived.

The data for the average reflectance of green beans are presented in Table XIX; the curves constructed from these data are shown in Figure 10; the trichromatic coefficients x and y (z is not included as $x + y + z = 1$); the dominant wavelength, brightness, and purity of the colors of these green beans are shown in Table XX. A few analyses of the color of carrots and of pole beans were made, and are recorded in Table XXI, although too few examinations were made to warrant discussion at this time.

Figure 10.

Average Reflectance Curves for Green Beans (White paper reference equal 100)

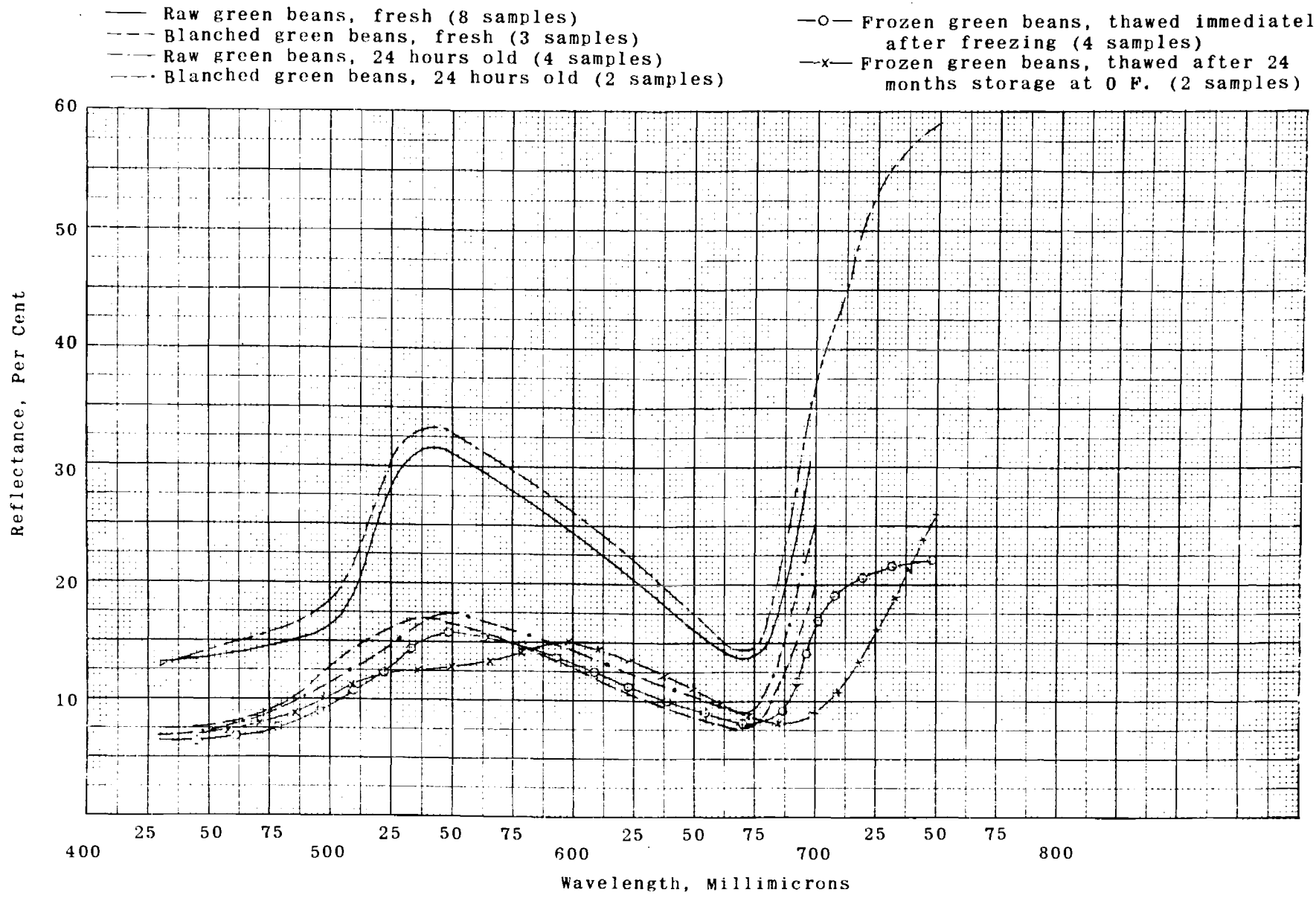


TABLE XIX

AVERAGE REFLECTANCE DATA FOR GREEN BEANS

Wavelength Millimicrons	Fresh Raw**	Fresh Blanched***	24 Hours Old Raw***	24 Hours Old Blanched***	Fresh Frozen**** Thawed After Freezing	Fresh Frozen*** Thawed After 24 Months Storage
430	13.5	6.7	13.3	7.5	6.9	6.9
500	16.7	12.9	18.0	11.3	9.7	10.7
540	31.8	16.6	33.9	17.9	16.1	12.9
600	24.6	12.9	26.3	14.6	13.5	14.5
675	14.0	7.9	14.1	8.8	8.4	8.8
700	35.0	25.8	37.8	25.5	18.2	9.4
725	----	----	54.0	----	21.5	16.5
750	----	----	59.0	----	22.5	26.0

* White paper reference equals 100 per cent.
** Average of nine samples.
*** Average of three samples.
**** Average of four samples.

TABLE XX

THE COLOR CHARACTERISTICS OF GREEN BEANS
DETERMINED BY REFLECTANCE BY THE I. C. I. METHOD*

Sample Number	Trichromatic Coefficients x	Trichromatic Coefficients y	Dominant Wavelength, Millimicrons	Purity, Per cent	Brightness,** Per cent
		Group I. Fresh, Raw Green Beans			
6	0.3494	0.4074	567	35	23.2
7	0.3509	0.4081	567	36	24.0
13	0.3509	0.4116	567	36	26.4
19	0.3507	0.4069	567	35	22.2
20	0.3548	0.4198	567	40	21.3
31	0.3472	0.4069	567	34	25.8
33	0.3519	0.4097	567	36	24.5
35	0.3539	0.4164	567	38	27.5
39	0.3577	0.3996	570	35	27.7

TABLE XX (Cont'd.)

THE COLOR CHARACTERISTICS OF GREEN BEANS
DETERMINED BY REFLECTANCE BY THE I. C. I. METHOD*

Sample Number	Trichromatic Coefficients x	Trichromatic Coefficients y	Dominant Wavelength, Millimicrons	Purity, Per cent	Brightness,** Per cent
		Group II. Fresh, Blanched Green Beans			
8	0.3427	0.4217	563	37	13.6
14	0.3472	0.4235	564	39	15.3
40	0.3305	0.4037	561	29	12.6
		Group III. Raw, Not Fresh Green Beans			
12 (1 day old)	0.3515	0.4071	568	35	26.8
38 (1 day old)	0.3543	0.4287	566	42	27.5
21 (2 days old)	0.3638	0.3981	572	36	23.4
43 (7 days old)	0.3650	0.4000	572	37	24.6

TABLE XX (Cont'd.)

Sample Number	Trichromatic Coefficients x	Trichromatic Coefficients y	Dominant Wavelength, Millimicrons	Purity, Per cent	Brightness** Per cent
Group IV. Blanched, Not Fresh Green Beans					
15(1 day old)	0.3484	0.4179	565	37	14.5
22(3 days old)	0.3515	0.4232	566	40	16.0
Group V. Fresh, Green Beans, Blanched, Frozen and Thawed on Same Day					
27	0.3594	0.4347	566	45	15.0
28	0.3745	0.4020	573	39	13.3
29	0.3416	0.3761	570	25	12.3
30	0.3498	0.3894	570	30	11.5
Group VI. Fresh Green Beans, Blanched and Frozen, Thawed after 24 Months Storage at 0° F.					
23	0.3612	0.3869	573	33	13.5
45	0.3680	0.4000	574	38	11.5

* Reflectance measurements made using white paper reference.

** Brightness values corrected on basis of impurity of white reference by multiplying the values obtained by 0.93.

TABLE XXI

THE COLOR CHARACTERISTICS OF CARROTS AND POLE BEANS
DETERMINED BY REFLECTANCE BY THE I. C. I. METHOD*

Sample Number**	Description of the Sample	Trichromatic Coefficients x	Trichromatic Coefficients y	Dominant Wavelength, Millimicrons	Purity, Per cent	Brightness*** Per cent
9	Fresh raw carrot	0.5277	0.3473	603	66.0	23.4
10	Fresh raw carrot	0.5280	0.3475	603	66.0	23.5
11	3-day-old raw carrot	0.4650	0.3770	590	58.0	26.9
16	Fresh raw pole beans	0.3543	0.4182	567	39.0	23.1
17	Fresh blanched pole beans	0.3419	0.4093	565	33.0	14.0
18	Fresh blanched pole beans	0.3474	0.4144	565	36.0	20.4
41	Fresh raw pole beans	0.3305	0.4018	561	28.5	17.5
42	Fresh blanched pole beans	0.3215	0.3967	558	25.0	8.6

* Reflectance measurements made using white paper refernece.
** Samples 9 and 10 from same lot; samples 16, 17, and 18 from same lot; samples 41 and 42 from same lot.
*** Brightness values corrected on basis of impurity of white paper reference by multiplying the values obtained by 0.93.

B. The Application of the Drying Rate Determination to the Estimation of Leakage in Peaches

1. Introduction

The results of previous work accomplished (Progress Report No. 19, pp. 4-13) on determining the drying rate of green beans with the Dietert Rapid Drier indicated that a correlation of drying rate with leakage could be obtained. Since, in the determination of leakage by immersion in mineral spirits, the removal of the fluid adhering to the surface of the sample probably represents the greatest source of error, it was hoped that the utilization of a drying method would eliminate this step.

2. The Determination of the Drying Rate of Peaches Using the Dietert Rapid Drier

Peach slices which had previously been frozen as 50-gram samples were removed from storage of 0° F. and placed immediately in the drier cup with the blower and heater in operation. For this experiment, the temperature of the air through the drier was maintained at 150° F. The samples were removed after 1/2-hour and weighed. Considerable fluid adhered to the peach slices. They were flipped three times each on three paper towels and reweighed. The per cent weight loss on the basis of a 50-gram sample and the total time of drying were recorded following each weighing. The results were reported here as the per cent weight loss for the total time of the drying and wiping instead of per cent weight loss per minute (as in Progress Report No. 19, pp. 4-13) in order to allow more direct comparison with leakage values, which are expressed as per cent weight loss. In Table XXII the results of drying tests run on slow frozen and rapid frozen peach slices

are compared with the leakage values obtained from similar samples of frozen peach slices by thawing under mineral spirits.

TABLE XXII

COMPARISON OF THE WEIGHT LOSS OF FROZEN PEACH SLICES BY THE DRYING* AND LEAKAGE METHOD**

		DRYING Weight Loss, Per Cent						LEAKAGE Weight Loss, Per Cent		
Method of Freezing	No. of Samples	Before Blotting Mean	SD	SE	After Blotting Mean	SD	SE	No. of Samples	Mean	SD
Slow***	4	19.2	1.0	0.5	41.8	4.8	2.4	15	26.4	4.8
Rapid****	4	13.2	1.1	0.5	23.0	3.5	1.7	10	17.0	4.8

*Drying determined as per cent weight loss by placing 50-gram sample in Dietert Rapid Drier maintained at 150° F. for 1/2-hour. Slices weighed, blotted (flipped three times each on three paper towels), and reweighed.

**Leakage determined as per cent weight loss by immersing peach slices in mineral spirits at 68° F. for four hours.

***Peach slices frozen in package in still air maintained at 0° F., five hours freezing time.

****Peach slices frozen loose by immersion in agitated alcohol bath maintained at -20° F., three minutes freezing time.

It may be concluded from these data that there is a significant difference between the drying values and between the leakage values for the two methods of freezing. The number of runs made was insufficient to draw a definite conclusion concerning a direct comparison of leakage and drying values, although the values obtained do indicate a direct correlation. However, no further drying of peach slices using the Dietert Rapid Drier was attempted since the air flow in that instrument was insufficient to remove adhering fluid from the peach slices before

final weighing.

3. Conversion of the Aminco Temperature Cabinet to a Drying Chamber

a. Introduction

The results of drying experiments using the Dietert Rapid Drier indicated the need for a warm chamber equipped with means for circulating air, in which several drying determinations could be made simultaneously. The Aminco Temperature Cabinet seemed suitable for this purpose. It is essentially an insulated cabinet having two compartments; one consists of a dry ice container with a blower; the other compartment constitutes a work chamber, and is equipped with a circulator fan and electrical heating coils. Each compartment has a separate insulated lid. A slide door between the two compartments allows the air from the dry ice compartment to be blown into the work compartment. Accurate temperature control in the range of -100° F. to 220° F. is maintained by a bimetallic thermoregulator which controls the operation of the dry ice fan and of the heater coils. (The interior of the Aminco box as used in this work is shown in Figure 11.)

b. Measurement of Air Flow in the Work Compartment of the Aminco Unit

In order to determine the uniformity of air circulation which could be obtained employing both the blower and the circulator fan, a thermocouple anemometer was prepared to measure the flow of air in several different locations in the work compartment. A source of approximately five volts A.C. was supplied to a Nichrome coil around the heated thermocouple by a Vari-tran transformer. A Weston microammeter (No. 11578) with a 30-ohm variable rheostat in parallel (to vary the

sensitivity of the microammeter) was connected in the thermocouple circuit. Adjustments were made so that a reading of 65 divisions was obtained on the microammeter when the anemometer was placed in still air. The anemometer zero was set at 20 divisions. The anemometer was placed in the work compartment with the circulator fan and blower running, and the lid to dry ice compartment open about two inches to permit free air circulation. The anemometer was then centered horizontally and successively positioned vertically four inches, 14 inches, and 22 inches from the bottom of the compartment. These three vertical positions correspond to the middle of the circulator level, midpoint between circulator and blower levels, and the center of the blower level, respectively. Readings were made at the three levels for each corner of the work compartment, and the results of these measurements are shown in Table XXIII.

TABLE XXIII

AIR FLOW IN WORK COMPARTMENT OF AMINCO UNIT

Vertical Level, Inches*	Decrease in Anemometer Reading			
	Corner 1**	Corner 2	Corner 3	Corner 4
22	27	22	16	15
14	13	20	12	15
4	14	13	15	17

*Vertical distance measured from bottom of work compartment.
**Corner 1 was adjacent to blower outlet with remaining corners numbered counterclockwise with respect to corner 1. All measurements were made approximately six inches from walls.

From these data it may be seen that the most uniform flow of air (as measured near the corners of the compartment) occurs at the four-inch level, corresponding to the middle of the circulator level. Additional readings were made at the four-inch level at locations other than the corners of the compartment, and no significant differences were observed at this level. Hence, it was concluded that the air flow in the work compartment four inches from the bottom and approximately six inches from the walls and heater coils was fairly uniform.

c. Adjustment of the Air Temperature in the Work Compartment of the Aminco Unit

A copper-constantan thermocouple and a Micromax recorder were employed to measure the air temperature in the work compartment of the Aminco unit. The thermocouple was located in the center of the work compartment four inches from the bottom level with the blower and circulator fan running, the thermostat controlling the heater coils set for maximum heat, and the lid to the dry ice compartment raised two inches to permit free air circulation. Although a temperature as high as 220° F. can be maintained with the lids to the work and dry ice compartments closed, the maximum temperature reached with the lid to the dry ice compartment slightly raised was 110° F. A 650-watt Ful-Kontrol laboratory heater was then placed in the dry ice compartment so that air entering the compartment through the lid opening passed over the coils of the heater and was blown into the work compartment through the slide door opening. The temperature control of the Ful-Kontrol heater was set for 60 per cent of maximum heat, and, with this additional heat, the temperature of the work compartment quickly rose to 150° F.

The addition of this constant source of heat made it possible to reduce the load on the Aminco heaters so that the thermostat for those heaters could be used for close control of the temperature at 150° F. The thermocouple was moved about to determine the temperature at a level four inches from the bottom of the work compartment. The results of this search are shown in Table XXIV.

TABLE XXIV

TEMPERATURE DISTRIBUTION IN WORK COMPARTMENT OF THE AMINCO UNIT

Location of Thermocouple	Temperature, °F.
Right rear*	151
Center rear	151
Left rear	151
Center	150
Right front	150
Center front	152
Left front	152

* For these temperature measurements, the wall separating the dry ice compartment from the work compartment was considered to be the rear wall of the work compartment. All measurements were made with the thermocouple approximately six inches from the walls of the compartment, excepting the center measurement.

These data presented indicate that a reasonably uniform temperature can be maintained at positions four inches from the bottom and six inches from the sides of the work compartment. The lid to the dry ice compartment was closed to permit the free operation of the work compartment lid. The lid to the work compartment was then opened for varying

periods of time to simulate the opening and closing necessary to introduce samples. The temperature changes caused by the different lengths of time the lid was open along with the time required for the temperature to return to normal were noted. These results are shown in Table XXV.

TABLE XXV

EFFECT OF INTRODUCTION OF SAMPLES ON THE TEMPERATURE* OF THE WORK COMPARTMENT OF THE AMINCO UNIT

Time Lid Open, Seconds	Minimum Temperature °F. Reached	Temperature Recovery Time, Seconds
30	120	40
60	112	40
120	112	300

* Original temperature of the work compartment was 150° F.
** Measurements made with thermocouple located in the center and four inches from the bottom of the work compartment.

It may be seen from the results presented that the temperature of the air in the work compartment is not seriously affected if the time required to introduce the sample is not more than one minute. It should be pointed out that the air temperature does not fall below 112° F. when the lid is open for a period of 120 seconds or longer, but the recovery time is excessive since the wall temperature as well as the air temperature has to be restored to the desired level.

d. The Sample Holder For Use in the Aminco Unit

A rectangular wooden frame 18 x 19 inches was fabricated and chalk line stretched tightly at 1/2-inch intervals around the top of the

frame so as to weave a support for samples which allows free circulation of air. The corded top was then varnished to strengthen and preserve the cord, and marked off into nine squares containing 36 square inches of area each. These squares were numbered, beginning in the upper left-hand corner, from left to right across the long side for the first row. As set up, this frame provides a holder which can accommodate nine samples while exposing a maximum surface area of each sample to the flow of warm air. The interior of the Aminco Unit (the lid removed) with the sample holder in place is shown in Figure 11.

4. Measurement of the Drying Rate of Peach Slices Using the Aminco Temperature Cabinet.

Several determinations of the drying rate of peaches were made employing wide variations in time lapse between removal of sample from storage and the beginning of drying, during which time samples were either immersed in mineral spirits at 68° F., or exposed to air at room temperature. In addition, the length of time of drying was also varied. The results of several drying rate determinations showing the varying conditions of each test are shown in Table XXVI. Since these results represent only a portion of a planned experiment, no discussion and analysis of the data will be made until the remaining determinations are completed.

C. The Determination of the Drying Rate of Green Beans Using the Aminco Temperature Cabinet.

Initial measurements of the drying rates of green beans using the Dietert Drier were reported in Progress Report 19 (pp.4-13). Since the use of the Dietert Drier allowed only a single run to be made at a time, it was decided to continue the investigation of the drying rate of green beans employing the Aminco Temperature Cabinet. In order to establish

Figure 11. View of Aminco Temperature Cabinet Showing the Sample Holder in Place

TABLE XXVI

THE DRYING RATE OF PEACHES

Sample Number	Number of Samples	Time Held in Air After Removal from 0° F. Storage, Minutes	Time Held in Mineral Spirits After Removal from 0° F. Storage, Minutes	Time Held in Aminco Box at 150° F., Minutes	Per cent Weight Loss			Drying* Rate
					Mean	SD	SE	
75**	9	10	0	30	29.6	±6.2	±2.1	0.98
75**	9	10	0	60	56.4	±5.7	±1.9	0.94
75**	9	25	0	30	32.4	±4.0	±1.33	1.08
62***	8	120	0	30	33.2	±5.2	±1.9	1.11
63***	8	0	0	15	2.9	±1.0	±0.37	0.12
63***	8	0	0	20	5.2	±1.8	±0.67	0.26
63***	7	0	0	30	11.5	±3.6	±1.3	0.38
63***	8	0	30	20	16.0	±4.4	±1.6	0.80
63***	7	0	60	20	14.4	±2.2	±0.95	0.72
63***	8	0	60	30	27.4	±2.5	±0.93	0.91

* Drying rate expressed as per cent weight loss per minute.
** Frozen slowly in package in still air at 0° F., five hours freezing time.
*** Samples No. 62 and 63 frozen rapidly by immersion in agitated alcohol bath maintained at -20° F., three minutes freezing time.

the conditions of the test which would give the most reproducible data, and, at the same time, indicate differences in processing, an experiment was planned, involving tests on slow frozen and rapid frozen green beans, during which the lapse of time between removal of sample from 0° F. storage and beginning of drying as well as the time of drying would be varied. Although the experiment has not been completed, the results of all runs made under various conditions are tabulated in Table XXVII. Certain portions of these data have been regrouped and are recorded in Tables XXVIII, XXIX, and XXX.

The data presented in Tables XXVIII, XXIX, and XXX indicate a possible significant difference between the values obtained for slow frozen green beans and rapid frozen green beans, the values for slow frozen green beans being larger than those for rapid frozen green beans for all conditions of thawing and drying time. Though not conclusive, the most reproducible results were obtained by employing a time lapse of four hours between removal of sample from 0° F. storage and initiation of drying, and allowing 30 minutes for drying at 150° F. However, no complete discussion and analysis of the data can be made until the remainder of the planned work has been accomplished.

D. Miscellaneous

The examination of samples which have been stored for 12 months at 0° F. was accomplished during the work period covered by this report. However, the tabulation and analysis of data have not been completed, and, therefore, the results of this examination will be reported at a later date.

TABLE XXVII

THE PER CENT MOISTURE LOSS OF
FROZEN GREEN BEANS UNDER VARIOUS CONDITIONS

Method of Freezing	n	Time of** Thawing	Time of Drying, Minutes	Moisture Loss, Per Cent*		
				Mean	SD	SE
Slow***	8		15	6.3	±4.0	±1.4
Slow***	8		30	14.2	±2.7	±1.0
Rapid****	9	5 minutes	30	13.0	±1.9	±0.63
Slow***	5	5 minutes	30	19.9	±1.0	±0.45
Rapid****	5	5 minutes	60	32.4	±2.6	±1.1
Slow***	5	5 minutes	60*	39.0	±3.3	±1.5
Slow***	6	5 minutes	60	42.0	±4.4	±2.5
Slow***	9	1 hour	30	19.3	±4.8	±1.6
Slow***	9	2 hours	30	18.4	±4.5	±1.5
Slow***	8	3 hours	30	16.3	±2.8	±1.0
Slow***	9	4 hours	30	18.5	±1.5	±0.5
Rapid****	4	4 hours	30	14.3	±1.0	±0.5
Rapid****	4	4 hours	60	37.8	±1.3	±0.65
Rapid****	8	5 hours	30	17.5	±2.0	±0.8
Rapid****	4	8 hours	30	16.6	±2.5	±1.2
Rapid****	8	8 hours	60	28.0	±3.8	±1.4

* Moisture loss determined as weight loss by placing 50-gram sample in air stream at 150° F. for specified length of time.

** Time lapse between removal of samples from 0° F. storage and placing in drier. Samples were exposed directly to air at room temperature for the five minute period, but were left in the cellophane bag during other thawing periods.

*** 50-gram samples frozen slowly in package in air at 0° F., about five hours time required to freeze.

**** 50-gram sample frozen rapidly by immersion in agitated alcohol maintained at -10° F., about three minutes freezing time required to lower temperature of sample to 0° F.

TABLE XXVIII

VARIATION IN MOISTURE LOSS FROM FROZEN GREEN BEANS WITH VARIATION IN TIME OF EXPOSURE TO AIR STREAM AT 150° F.

Time of Exposure, Minutes	Moisture Loss, Per Cent: Slow Frozen,* Thawed in Drier for Five Minutes				Rapid Frozen,** Thawed in Drier for Five Minutes			
	n	Mean	SD	SE	n	Mean	SD	SE
30	5	19.9	±1.0	±0.45	5	13.0	±1.9	±0.63
60	6	42.0	±4.4	±2.5	5	32.4	±2.6	±1.1

* 50-gram sample frozen slowly in package in air at 0°F., about five hours freezing time.

** 50-gram sample frozen rapidly in agitated alcohol maintained at -10° F., about three minutes freezing time required to lower temperature of sample to 0° F.

TABLE XXIX

MOISTURE LOSS FROM FROZEN GREEN BEANS EXPOSED TO AIR STREAM AT 150° F. FOR 30 MINUTES

Moisture Loss, Per Cent: Slow Frozen,* Thawed in Cellophane Bag in Air for Four Hours				Rapid Frozen,** Thawed in Cellophane Bag in Air for Four Hours			
n	Mean	SD	SE	n	Mean	SD	SE
9	18.5	±1.5	±0.5	4	14.3	±1.0	±0.5

* 50-gram sample frozen slowly in package in air at 0° F., about five hours freezing time.

** 50-gram sample frozen rapidly in agitated alcohol maintained at -10° F., about three minutes freezing time required to lower temperature of sample to 0° F.

TABLE XXX

VARIATION IN MOISTURE LOSS FROM FROZEN GREEN BEANS WITH VARIATION IN TIME LAPSE BETWEEN REMOVAL OF SAMPLE FROM 0° F. STORAGE AND INITIATION OF DRYING

Time Allowed for Thaw	Moisture Loss Due to 30 Minutes Exposure to Air Stream at 150° F., Per Cent						
	Slow Frozen*			Rapid Frozen**			
	n	Mean	SD	SE	n	Mean	SD	SE
0	8	14.2	±2.7	±1.0				
5 minutes***	5	19.9	±1.0	±0.45	9	13.0	±1.9	±0.63
1 hour	9	19.2	±4.8	±1.6				
2 hours	9	18.4	±4.5	±1.5				
3 hours	8	16.3	±2.8	±1.0				
4 hours	9	18.5	±1.5	±0.5	4	14.3	±1.0	±0.5
5 hours					8	17.5	±2.0	±0.8
8 hours					4	16.1	±2.5	±1.2

* 50-gram sample frozen slowly in air at 0° F., about five hours freezing time.

** 50-gram sample frozen rapidly in agitated alcohol maintained at -10° F., about three minutes freezing time required to lower temperature of sample to 0° F.

*** Sample thawed in drier for five minutes. Thawing times greater than five minutes represent the time the sample was exposed in the cellophane bag in air at room temperature prior to placing in the drier.

III. FUTURE WORK

It is planned that the work for the next three months will consist of (1) the further study of the physical characteristics of green beans, especially by the determination of drying rate; (2) the continuation of the application of the drying rate in estimating leakage in peaches; (3) the continuation of the measurement of color of food products by reflectance; and (4) the completion of the tabulation and analysis of data pertaining to the examination of frozen samples stored 12 months.

Respectfully submitted;

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APPENDIX

THE METHOD OF COLOR SPECIFICATION ADOPTED BY THE INTERNATIONAL COMMISSION ON ILLUMINATION[1]

In order to see an object and its color the object must be illuminated by a source of light either natural, such as the sun, or artificial, such as the tungsten lamp. These light sources radiate energy in the form of waves which differ in length according to the color. Wavelength is measured from crest to crest of the light waves and the unit of length commonly employed for specifying the wavelength of visible radiation is the millimicron. Although the human eye is capable of detecting light waves from 380 to 770 millimicrons in length, the amount of radiant energy the eye can detect below 400 and above 700 millimicrons is very limited and, consequently, it has become standard to report light responses of the visible region only between these latter wavelengths.

When the light from the sun or tungesten lamp is passed through a prism, the "white" light is dispersed and separated into its component colors and the familiar spectrum extending from violet through blue, green, and yellow to red may be perceived. In terms of the millimicron unit of wavelength, these spectral regions comprise approximately the following ranges:

Violet	400-450 Millimicrons
Blue	450-500 Millimicrons
Green	500-570 Millimicrons
Yellow	570-590 Millimicrons
Orange	590-610 Millimicrons
Red	610-700 Millimicrons

[1] This discussion is based primarily on the work of A. C. Hardy, Handbook of Colorimetry. The Technology Press, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1936.

This subdivision of the visible spectrum into six regions is a rather arbitrary procedure since the color of the spectrum actually varies continously throughout its length. The colored object appears colored because it does not reflect all the light that falls on it; the remainder of the light falling on the colored object is either transmitted through to the other side and lost, or is absorbed. A green object, then, reflects the green portion of the light falling on it, and absorbs or transmits the remainder of the light. It is evident that the visual stimulation received from a colored surface will depend upon the character of the light illuminating that surface.

The spectrophotometer provides a precise objective method of evaluating the color of objects by determining the light reflected (or transmitted) by a colored object using a standard light source. When a single spectral component of light is impinged upon an object, the surface of that object cannot reflect more of that component than falls upon it and the reflection factor of the surface for that light component is one of the inherent properties of that surface. This same phenomenon is true for all the other individual components of the spectrum. Therefore, a purely objective measurement of the color of a surface can be made in terms of the reflection factor for each individual component. The result of comparing the light reflected by a colored object with a standard light source is the spectral response curve for that object and is usually recorded as a graph, with reflectance (or transmission) as the ordinate axis and wavelength as the abscissa axis. A typical spectral response curve for green beans is shown in Figure 12. Such curves may be obtained by making measurements for as many wavelength regions as the nature of the problem requires, and every possible color

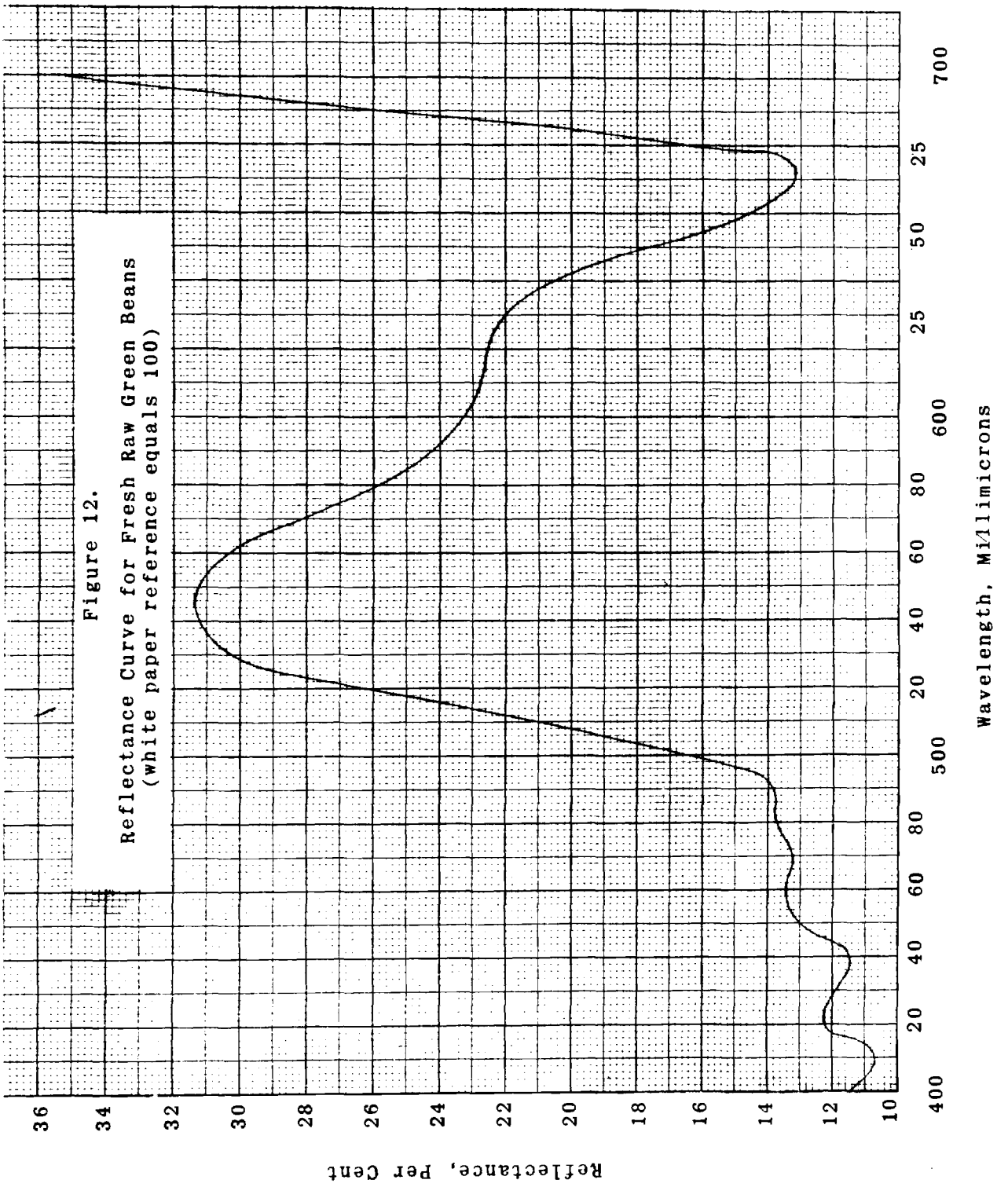


Figure 12.
Reflectance Curve for Fresh Raw Green Beans
(white paper reference equals 100)

attribute of an object can be represented by a curve of this type. The values of the reflection factor are referred to a white standard whose factor is 1.00 for all wavelengths so that a perfectly white surface, which reflects completely all the visible radiations falling upon it, would be represented by a horizontal line at the top of the graph. On this same basis, an absolutly black surface would be represented by a horizontal line at the bottom.

Although the spectrophotometer will allow precise measurements of the color of an object which serve as a color record, the spectrophotometer, or spectral response, curve is not a description in itself, but serves as a basis for evaluating the stimulation that results under any set of specified conditions. Certain manipulations must be performed with the data presented by the spectral response curves in order to arrive at color specifications. Color may be evaluated in terms of certain standard or primary stimuli. A normal observer may duplicate the effect of any color stimulus by mixing the light from three primary sources in the proper proportions, and only one combination of the three colored lights used to match the test color will accomplish this match. By calibrating the controls which determine the amount of each color stimulus employed, the amount of each color may be recorded. These three matching colors are known as primary stimuli, and the amount of each required to make a match are known as the tristimulus values which are specified by three numbers X, Y, Z. These X, Y, and Z values for any color may be determined by employment of a normal observer and a colorimeter. However, in order to see color it must be illuminated and to obviate the irregularities of observed results, three sources of light were standardized and adopted in 1931 by the Inter-

national Commission on Illumination (I. C. I.). The most commonly used illuminant is Illuminant C, an approximation of average daylight (sun plus sky light). Also, the subject illuminated by a standard illuminant must be perceived in a uniform manner so that the interpretation of the perception is in terms universally acceptable and understandable. A "standard observer" has therefore, likewise, been specified by the I. C. I. as an individual who is presumed to have completely normal eyesight, and colors are specified in terms of the standard observer. Since the mechanism of the human eye is such that few persons see color alike, the common denominator of observations of a large group of observers carefully selected for normal vision was obtained to furnish basic color mixture data which were used in conjunction with spectrophotometric data to compute for any test sample the average tristimulus values that would have been obtained by this group of observers had they used a colorimeter. Since the readings obtained with a spectrophometer are independent of the peculiarities of an observer's eye, this procedure provides a basis for the specification of color in terms of the average chromatic properties of an internationally accepted group of observers.

The procedure used to interpret spectrophotometric data demands that first the tristimulus values be determined for wavelengths throughout the entire visible spectrum. This was accomplished by matching very narrow sections of the visible spectrum with the primary stimuli, and the tristimulus values of the spectrum which had been adopted by the I. C. I.. The relationship between the tristimulus values for the various spectrum colors is shown in Figure 13. by plotting wavelength versus the tristimulus values. It should be pointed out that no set of real

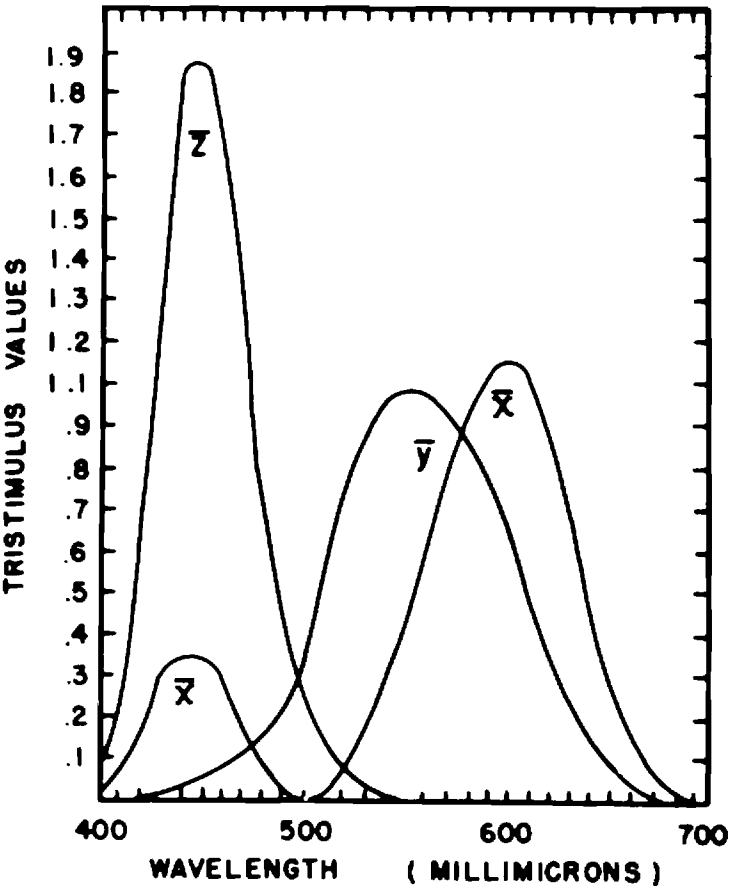


Figure 13. Relationship between the Tristimulus Values of the Spectrum Colors

primaries can be found that will match all colors without employing negative amounts of at least one of the primaries and that the above values were based on primaries outside the realm of real colors so that none of the values are negative. The value X represents the amount of a primary which is a reddish purple of higher saturation than any obtainable color having this hue. The value Y represents the amount of a green primary considerably more saturated than the spectrum color whose wavelength is 520 millimicrons. The value Z represents the amount of a blue primary that is considerably more saturated than the spectrum color whose wave length is 477 millimicrons. Also, in transforming the data obtained with actual primaries to a set of primaries that would avoid negative tristimulus values, a set of primaries were chosen which made the Y function correspond to visability or brightness. Hence, the relative brightness of a sample is indicated directly by the value of Y on a scale that represents an absolute black by zero and a perfect white by 100.

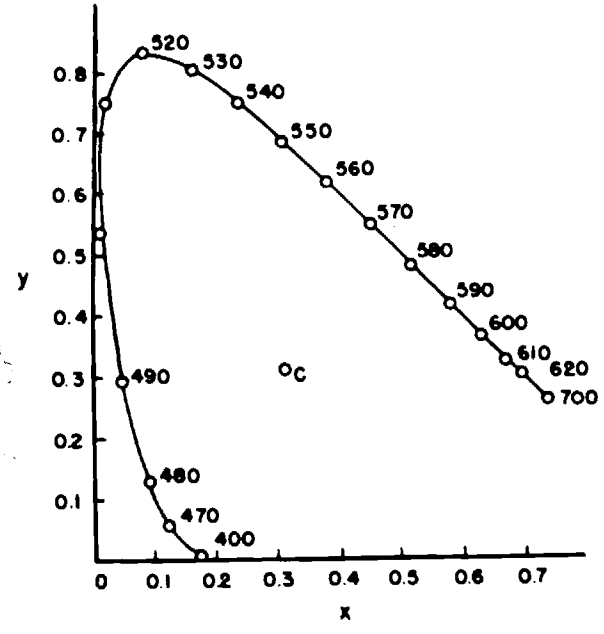
In order to fully evaluate the quality of a color, it is necessary to define color in terms of its chromaticity. Trichromatic coefficients, or coordinates, may be determined as follows:

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z} \qquad (1)$$
$$z = \frac{Z}{X+Y+Z}$$

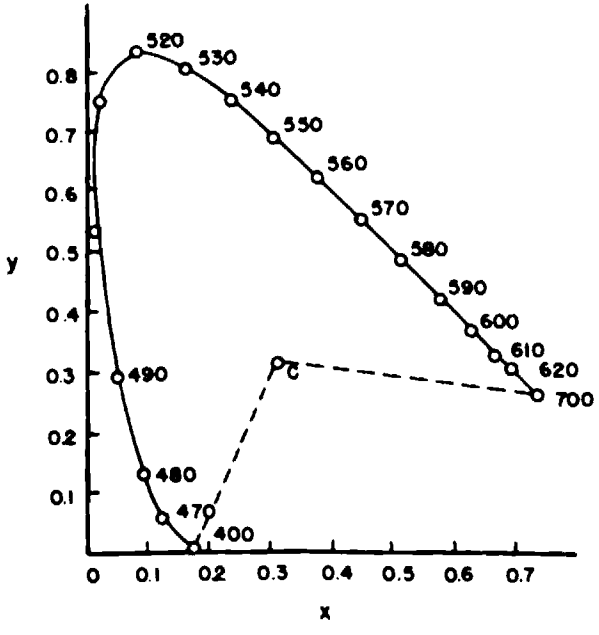
Also, $$x+y+z = 1 \qquad (2)$$

Hence color may be specified by giving values of only x and y along with the term Y, the brightness factor. The addition of Y is necessary since two colors may have the same chromaticity and only differ

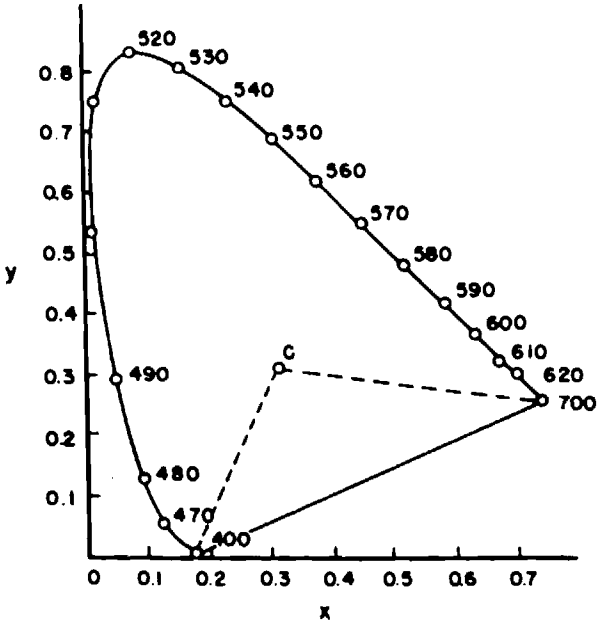
in brightness. To further locate the color in question with reference to all other colors, it is convenient to graphically represent the relationship of various colors one to another. Since the three dimensional plot indicated is rather impractical and the sum of x, y, and z is always unity, it is customary to construct a two dimensional plot of the trichromatic coefficients, x and y. Such a plot is referred to as a color diagram, or a chromaticity diagram. The plot of the trichromatic coordinates of several of the spectrum colors, connected with a smooth line, is given in Figure 14A. The solid line joining the various spectrum colors is known as the spectrum locus, and on it is located every color of the spectrum. Since a nonselective specimen, that is, one having constant reflectance or transmission throughout the visible spectrum, would assume the color of the light source under which it is viewed, the trichromatic coefficients of the light source used may be plotted as the center of the chromaticity diagram. The point marked C in Figure 14A is the location of Illuminant C. By connecting the two ends of the spectrum locus to the light source with dotted lines as shown in Figure 14B, the area enclosed will include equivalent stimuli for all colors that could be made by mixtures of light from the illuminant and light from any region of the spectrum. The nonspectrum colors such as the purples may be located on an additional section of the color map in the area formed between a line joining the two ends of the spectrum locus and the dotted lines from the illuminant to the ends of the spectrum locus, as shown in Figure 14C. The colors lying in this area are thought of as a mixture of red and violet light together with light from the illuminant. The wavelength of light which must be mixed with the illuminant to produce a desired color is referred



A. Spectrum Locus and Illuminant C.



B. Area of Equivalent Stimuli for all Spectrum Colors.



C. Area of Equivalent Stimuli for Spectrum Colors and Mixtures of Violet and Red Light (Purples).

Figure 14. The Chromaticity Diagram

to as the dominant wavelength of that particular color. The numerical specification of the purity (excitation purity, rather than colorimetric) of the sample may be determined by obtaining the percentage ratio of the distance of the color point and of the intersection of the spectrum locus from the illuminant point.

The interpretation of the spectrophotometric curves in terms of tristimulus values requires that one multiply the spectral reflectance curve for the color by the spectral energy distribution curve for the illuminant. This product curve must then be multiplied separately by each of the curves of Figure 13. The areas under these curves are designated as X, Y, and Z. However, in actual practice, the computations may be performed by using a selected ordinate method developed by Hardy[1] whereby ten (also systems for 30, 100, etc.) readings of the reflectance (or transmission) of the spectrophotometric curve at various wavelengths are made for each primary stimulus; the sum of these readings is multiplied by a correction factor and the product is the tristimulus value. Tristimulus coordinates are then obtained by means of equations having the same form as (1). The tristimulus coordinates x and y may then be used to locate the color in question on a set of color charts or maps based on the I. C. I. observed and Illuminant C. By this treatment, the specification of color in terms of dominant wavelength, purity, and brightness may be obtained.

Georgia Institute of Technology
STATE ENGINEERING EXPERIMENT STATION
Atlanta, Georgia

PROGRESS REPORT NO. 23

PROJECT NO. 98

FOOD PRESERVATION

Prepared For

TENNESSEE VALLEY AUTHORITY

By

F. BELLINGER and T. W. KETHLEY

JULY 1, 1949--FEBRUARY 28, 1950

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TABLE OF CONTENTS

This Report Contains 35 Pages

I. SUMMARY

Employing a rotating disc sample holder and spectrophotometer, the reflectance analysis of the color of green beans in various conditions of maturity and processing has been completed. This work was carried out because of the importance of color in the marketing of foods, and because changes in color always accompany other changes in foods. As the visually observed color of a food is due partially to the physical arrangement of the pigment materials at the surface of the tissue and to the physical condition of the tissue surfaces, observations made on extracts and purees do not necessarily depict accurately the visually observed color.

Although previous work indicated that the color of green beans could be characterized from reflectance data at three critical wavelengths, no satisfactory mathematical statement was derived to express these results. The present work was carried out to establish the treatment of the data necessary to obtain a mathematical statement which would describe adequately the color condition of the beans in a manner which could be correlated with visual observations.

It was found that a series of rather pronounced color changes, perceptible to human observers, occurswhen beans are cooked for varying lengths of time. This method of accelerated aging was employed in an attempt to establish a standard curve in much the same manner as transmission data from standard solutions are employed in the colorimetric analysis of solutions. The reflectance data obtained from cooked green beans at the three critical wavelengths (430, 540, and 675

millimicrons) were then examined and mathematically treated until a single index was derived, which numerically could be correlated with visual observations. This index is a function of that area under the color curve which falls within a triangle whose vertices are the reflectance values obtained at 430, 540, and 675 millimicrons. This index has been referred to as the area of the color triangle.

Because the numerical values for the area of the color triangle correlate with visually observed changes in the color of green beans during cooling, it has been possible to describe the color of green beans in terms of equivalent cooking time. It was found that the color changes occurring in green beans during maturation, processing, and freezing storage could be described in these terms. These findings suggest the possibility of employing samples of green beans cooked for various lengths of time for the establishment of color standards not only for instrumental analysis, but also for visual comparison.

Although the experimental work reported deals exclusively with green beans, the results are directly applicable to most green vegetables; the general procedure is applicable to the analysis of the color of the intact surface of practically all foods, and possibly to many other colored materials.

Work has been initiated on the development of a simplified reflectance meter for field use in the collection of data for the calculation of the area of the color triangle. One such meter has been made and preliminary tests prove that the basic idea is practical, although the present model is not considered suitable for field use

because of the low numerical readings obtained from it and the high light intensity required. Work is planned which should lead to the development of a more satisfactory instrument.

II. EXPERIMENTAL WORK

A. The Formulation of an Index for the Color of Green Beans Under Various Conditions

As set forth in the work plans for this project for the current year, the first objective was the establishment of standards for the color of green beans under various conditions. Because of the extreme complexity of the very nature of color, the methods commonly used to describe a color numerically and completely involve three variables. In using such descriptions only the most experienced operators are capable of making distinctions between colors, and the determination of color differences is time consuming and laborious. For these reasons it has been felt that a method of specifying color which would be useful in the grading of fruits and vegetables should be more simple and, if possible, employ a single mathematical statement.

A great deal of time was spent in an attempt to formulate such an index, employing data collected in the summer and fall of 1949. Because of the great possibilities of the application of such an index, the results of these studies have been prepared in the form of an article to be offered for publication. The first draft of this article appears as the Appendix to this report. This article shows that a single numerical index can be obtained and that this index will adequately describe the color of green beans (and most other green vegetables) under various conditions of maturity and processing.

B. Developmental Work on a Simplified Reflectance Meter

A suitable index for the description of the color of green beans having been developed, work was immediately initiated on the development

of a simplified instrument for the collection of data necessary for the calculation of such an index. As shown in the article in the Appendix, these data are reflectance values at 430, 540, and 675 millimicrons. Because of the necessity of collecting information of reflectance for relatively narrow bandwidths, interference filters were ordered for these wavelengths. The filters obtained were manufactured by Baird Associates and have the characteristics shown in Table 1. The information given in the table shows that these filters permit the passage of light of only a very narrow band and that the per cent of light transmitted at the maximum is relatively low. This latter fact indicates that the primary light source would have to be very intense in order to pass sufficient light through the filters for practical considerations.

Although photoelectric cells are extremely sensitive to light, the cost of an amplifier for such a cell is probably prohibitive for a field instrument. For this reason the relatively inexpensive photronic cell manufactured by Weston Instrument Company was selected for this purpose. In order to determine the response characteristics of this cell to varying intensities of light, the cell was connected to a low-resistance microammeter and placed directly beneath the lens of a photographic enlarger. A 500-watt photo-flood bulb was used in the enlarger. Quantitative variation of the light intensity on the photocell was obtained by a variation of the lens stop on the enlarger lens. The response of the cell was checked for each of the interference filters, and the resulting data are shown in Table II. If these data

TABLE 1

CHARACTERISTICS OF THREE INTERFERENCE FILTERS

Filter Number	Transmission Peak Desired	Wavelength of Maximum Transmission	Per Cent Light Transmitted at Maximum	Wavelength Range of 33.3% Maximum
4330-6390 A°	430 mμ	433 mμ	27.0	426-440 mμ
3710-5395 A°	540 mμ	542 mμ	40.5	532-552 mμ
4560-6745 A°	675 mμ	675 mμ	34.0	662-682 mμ

are plotted on log-log paper, three parallel straight lines are obtained, indicating a linear response of the photronic cell.

Although a number of arrangements were corsidered for the design of the first simple reflectance meter, it was decided to work in a darkened room before a model was actually constructed, thus eliminating the need for a light-tight housing. Properly defined, reflectance is expressed in terms of light incident 45° to the sample and reflected 90° to the sample. To meet these conditions, a large microscope lamp was equipped with a metal yoke to which the photronic cell was mounted so that the surface of the photronic cell was 45° to the axis of the light beam of the lamp. The microscope lamp was fitted with a 500-watt prefocused base lamp and was air-cooled to prevent over-heating. With the relation of the cell and the lamp thus fixed, the proper conditions for reflectance measurements could be obtained whenever the face of the cell was placed parallel to and above the sample. A simple slide drawer with spring clips was mounted to the cell to accommodate the interference filters.

The proper spacing between the face of the photronic cell and the surface of the sample was determined from an estimation of the relative amount of light reflected 90° to the sample when the photronic cell was held at various distances from the sample. It was found that when the lower edge of the cell mounting was positioned 2.25 inches from the surface of the sample, the center of the light spot on the sample was directly beneath the center of the photronic cell, and that light reflected 90° from a smooth sample was received by the cell. In this

TABLE II

RESPONSE OF MODEL 594 PHOTRONIC CELL
TO VARIATIONS IN LIGHT INTENSITY

Photographic Enlarger Lens Stop	Reading of Microammeter (50 Ohms Internal Resistance) 430 mμ Filter	540 mμ Filter	675 mμ Filter
4.5	63	150	110
5.6	44	120	86
8	21	57	38
11	12	31	20
16	6	15	10
22	3	9	5
32	2	5	3

case, the light spot on the sample was an ellipse, 3.25 x 2.5 inches. The photronic cell was circular in shape, being 1.6 inches in diameter. Thus, for a smooth sample, the equipment setup described here, the "R-meter," was able to "see" on the sample a circular area 1.6 inches in diameter.

A 12-inch-diameter color disc was prepared from wedge-shaped segments of colored art paper mounted on the turntable of a hand-wound portable phonograph. The phonograph has an adjustable governor so that it was possible to vary the speed of the turntable from 35 rpm to 80 rpm as desired. When the R-meter was properly positioned above this color disc, it was noted that the needle of the microammeter of the R-meter wavered only slightly if the sample was rotated at about 70 rpm. The readings made when the color disc was rotated were numerically equivalent to the average of the readings made on sheets of the art

paper from which the color disc was made. All the values obtained were numerically low, indicating that either a greater light intensity was required or a more sensitive photocell would be necessary for field use. However, they were sufficiently large to warrant an investigation of the practicability of an instrument of this type for color analysis.

To determine the correlation between R-meter readings and spectrophotometer readings, a large series of examinations was made on various grades of rough colored paper. It was found that the values obtained with the R-meter when the 430 and 540 mμ interference filters were used correlated well with spectrophotometric observations. However, there were some readings obtained from the R-meter with the 675 mμ interference filter which did not correlate with spectrophotometric observations. A thorough analysis of these cases (including a complete spectrophotometric analysis) showed no real cause for this situation, although the analysis indicated that the apparent error might be due to the fact that the interference filters have a wider spectral band than normally employed on the spectrophotometer. It was further found that, when green beans were studied, no such discrepancy existed between the data obtained from the R-meter and those obtained from the spectrophotometer.

Only two sets of samples of green beans have been examined to determine the area of the color triangle by use of the R-meter. These data are shown in Table III. It was found that satisfactory readings could be made with the R-meter without the sample's being rotated, because of the large area "seen" by the photronic cell. Unfortunately, the

numerical values obtained were so small that considerable error could arise from the manner in which the meter is read, and, also, the use of a 500-watt bulb requires air cooling. These militate against the use of the present R-meter in the field, although the fact that sample rotation is not required is a desirable characteristic.

TABLE III

THE AREA OF THE COLOR TRIANGLE FOR GREEN BEANS, AS DETERMINED FROM DATA OBTAINED BY USE OF THE R-METER AND THE SPECTROPHOTOMETER

Sample Description	Area of the Color Triangle	
	By the R-Meter*	By the Spectro-photometer**
Green beans, frozen 3 months, thawed	4.35	4.04
Green beans, frozen 28 months, thawed	7.73	6.79

*Sample not rotated.
**Sample rotated at 370 rpm.

The evidence collected to date indicates that the area of the color triangle can be accurately estimated from data obtained from a simplified reflectance meter. In order to obtain better operating characteristics than those found in the present R-meter, several approaches remain to be tried. Although some glass filters were tried with the R-meter and found to be useless, the possibilities of this type of filter have not been exhausted. Glass filters would permit the passage of a greater amount of light and, thus, permit the use of a smaller light source. On the

other hand, a lens system might be devised to collect the reflected light, or a more sensitive photocell might be employed. However, any one of these stratagems would require the use of equipment more costly than that used in the present R-meter.

III. FUTURE WORK

It will be necessary to overhaul all the equipment used in the analysis of color before further work can be accomplished. As soon as this has been carried out, the developmental work on the simplified reflectance meter will be continued.

Respectfully submitted:

F. Bellinger,
Project Director

T. W. Kethley,
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Approved:

Gerald A. Rosselot, Director
State Engineering Experiment Station

IV. APPENDIX

MEASUREMENT AND ANALYSIS OF THE COLOR OF GREEN BEANS*

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ABSTRACT

Employing data obtained from the measurement of the reflectance of the intact surface of green beans on a rotating disc sample holder, a numerical index has been derived which adequately describes the color changes in green beans caused by maturation, processing, and freezing storage. It has been found that beans cooked for predetermined lengths of time can be used as color standards either for visual or instrumental estimation of color changes in green beans. These findings are directly applicable to the color grading of most green vegetables and the general procedure should be applicable to the color grading of foods and other colored materials.

INTRODUCTION

During the course of investigations on the fundamental changes brought about in foods by freezing perservation it has been noted that the visually observed color of the food is affected by processing and freezing storage. The measurement and analysis of the color of foods,

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*From a project sponsored jointly by the Georgia Tech Engineering Experiment Station and the Food Processing Section of the Tennessee Valley Authority.

therefore, has assumed considerable importance as a possible method of evaluating these changes. Because the visually observed color of a food is due partially to the physical arrangement of the pigment materials at the surface of the tissue and to the physical condition of the tissue surfaces, observations made on extracts and purees do not necessarily depict accurately the visually observed color. Hence, the measurement and analysis of the color of the intact surface of foods is of interest to all research groups studying the preservation of foods, as well as to those workers responsible for quality control in the food processing industries.

The problem of sampling and collecting data on the color of the intact surfaces of foods by reflection have been discussed in previous papers (2,3). This earlier work showed that the reflected color of the intact surface of green beans could be measured if the beans were placed on a disc and rotated during the process of measuring.

Although the preliminary work indicated that the color of green beans could be characterized from reflectance data at three critical wavelengths, no satisfactory mathematical statement has been derived to express these results. The present work was carried out to establish the treatment of the data necessary to obtain a mathematical statement which would adequately describe the color condition of the beans in a manner which could be correlated with visual observations.

In order to obtain data to be treated, it was necessary to follow and record visual color changes in samples from the same lot of beans. Shifts in color recorded by comparing color photographs of stored

frozen beans with color photographs made of the sample prior to freezing (1) indicated that there was no direct correlation between the time of storage and the amount of color change. However, it was found that a series of rather pronounced color changes, perceptible to human observers, occur when beans are cooked for varying periods of time. This method of accelerated aging was then employed in an attempt to determine a "standard curve" in much the same manner as transmission data from standard samples are employed in the colorimetric analysis of solutions. After visual studies were made to determine the times of cooking required to cause perceptible changes, large samples of beans were cooked for these periods of time, visual observations were recorded, and reflectance examinations were carried out.

Previous work (2,3) on green beans had shown that reflectance measurements at three specific wavelengths--430, 540, and 675 millimicrons--characterized the color of green beans. Also, of the mathematical methods of treatment previously examined, the two most promising seemed to be either the examination of the profile of the color curve or the estimation of the color in terms of reflectance measurements at a single wavelength. This paper presents the treatment of data by the above methods and the derivation of a single mathematical statement which apparently characterizes the color changes of green beans during cooking, as well as during frozen storage.

MATERIALS AND METHODS

Green beans were used as the test food for all measurements because they are representative of the green vegetables most commonly preserved by freezing and are usually available throughout the year. The rotating disc and spectrophotometer (Beckman model Du and No. 2580 reflectance accessory) described earlier (2) were employed for the measurement of the color of the beans. Measurements were made at the three critical wavelengths 430, 540, and 675 millimicrons, slit widths being 0.5, 0.3, 0.5 mm, respectively, based on a block of white vitrolite furnished by the National Bureau of Standards as the standard. Examinations were made first on beans which had been cooked for varying lengths of time, these having been determined by cooking several lots of beans and visually observing the lapse of time required to bring about discernible changes in the color of the beans. The most outstanding color changes were observed to take place at the end of 1, 3, 5, 8, 15, 20, 25, and 30 minutes. The color changes from 20 to 30 minutes were very slight, although the other changes were quite definite. In order to insure uniformity, the beans were distributed in a single layer in a small steam chamber and cooked at 212° F. As soon as the beans were cooled, they were placed on the needles of the rotating disc and the color was measured.

In addition to the observations made on cooked beans, examinations were carried out on raw and blanched (three minutes in steam), on blanched, frozen, and thawed beans (both fresh and 48 hours after picking), and on beans in various stages of maturity.

THE DERIVATION OF AN INDEX

To be useful in quality control, a mathematical statement employed to picture a change in the material in question must have certain basic characteristics. Such a statement must first refer to the true condition of the product in a manner which can be correlated with independent observations derived from some other source--in this case, from visual examinations. This correlation is preferably linear, although nonlinear correlation can be used if necessary. In the second place, a statement must be capable of a certain order of reproducibility, determined by the needs of the situation at hand. Thus, in the case of green beans, the order of reproducibility of a mathematical statement concerning beans cooked for five minutes must be greater than the difference between the mathematical statement for beans cooked five minutes and that for beans cooked eight minutes, because the visual examination of cooked beans shows a discernible difference between the color of beans cooked five minutes and that of beans cooked eight minutes. The third requirement for a mathematical statement is that it should have the greatest possible change in numerical value with observed changes in quality.

In the derivation of an index, preliminary treatment was carried out by a plot of the various data and derived data on graph paper to show the trend of correlation. As indicated above, certain periods of cooking caused discernible changes in the color of green beans, and for this reason the plots were made in terms of cooking times, rather than in terms of specifically observed color changes. The first plots are shown in Figure 1, where the readings at 430, 540, and 675 millimicrons

are plotted on linear coordinate paper against the time of cooking. Three different lots of green beans are represented by these data, each lot being indicated by a different symbol. At this point it should be noted that the lot of green beans indicated by an X in this figure (and in succeeding figures) was reported to have an appearance slightly different from that of the other two lots. This observation is reflected in the tendency of the data for this particular lot to cluster away from the data for the other two lots, particularly for the readings made at 540 millimicrons. Even the most casual inspection of the curves in Figure 1 will show that the readings made at 540 millimicrons are better correlated with increasing time of cooking than are the readings made at 430 or 675 millimicrons.

Two derived mathematical statements are shown plotted in Figure 2, again times of cooking being the ordinates. These two mathematical statements are as follows: (1) the reading made at 540 millimicrons was divided by the reading made at 675 millimicrons for a particular sample of green beans (this factor was then multiplied by 50 because the pooled average for fresh, raw beans treated in this manner was found to be 100); (2) the reading made at 675 millimicrons for the sample was divided by the 675 reading made on fresh raw beans and multiplied by 100. These particular mathematical treatments were made because the 675 reading on green beans appears to be associated almost exclusively with the chlorophyll of the beans, and the 540 millimicron reading appears to be associated with both carotenoids and chlorophyll. Inspection of the data plotted in Figure 2 shows that there is a distinct difference in

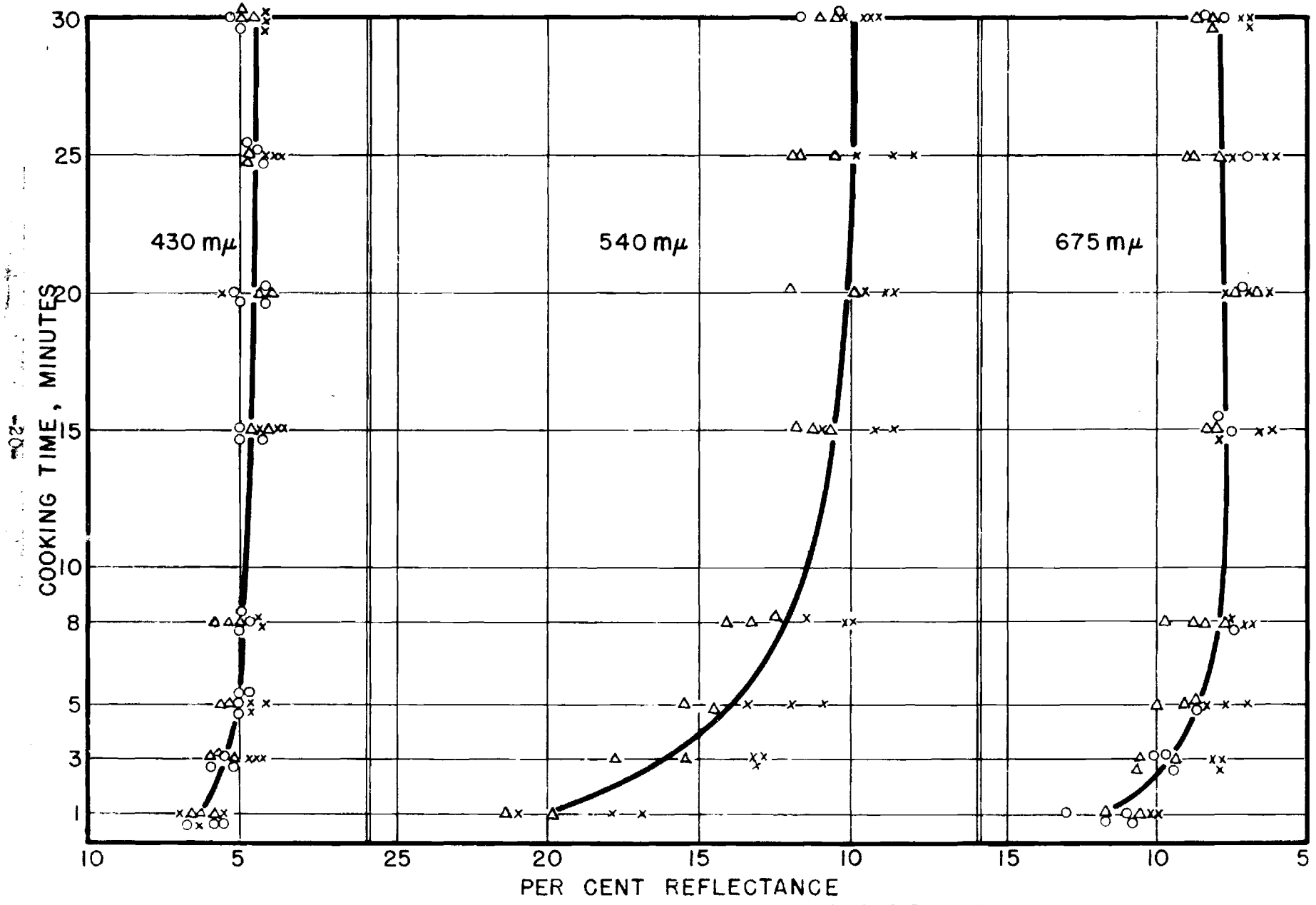

Figure 1. Reflectance Data Obtained From Cooked Green Beans at 430, 540 and 675 Millimicrons

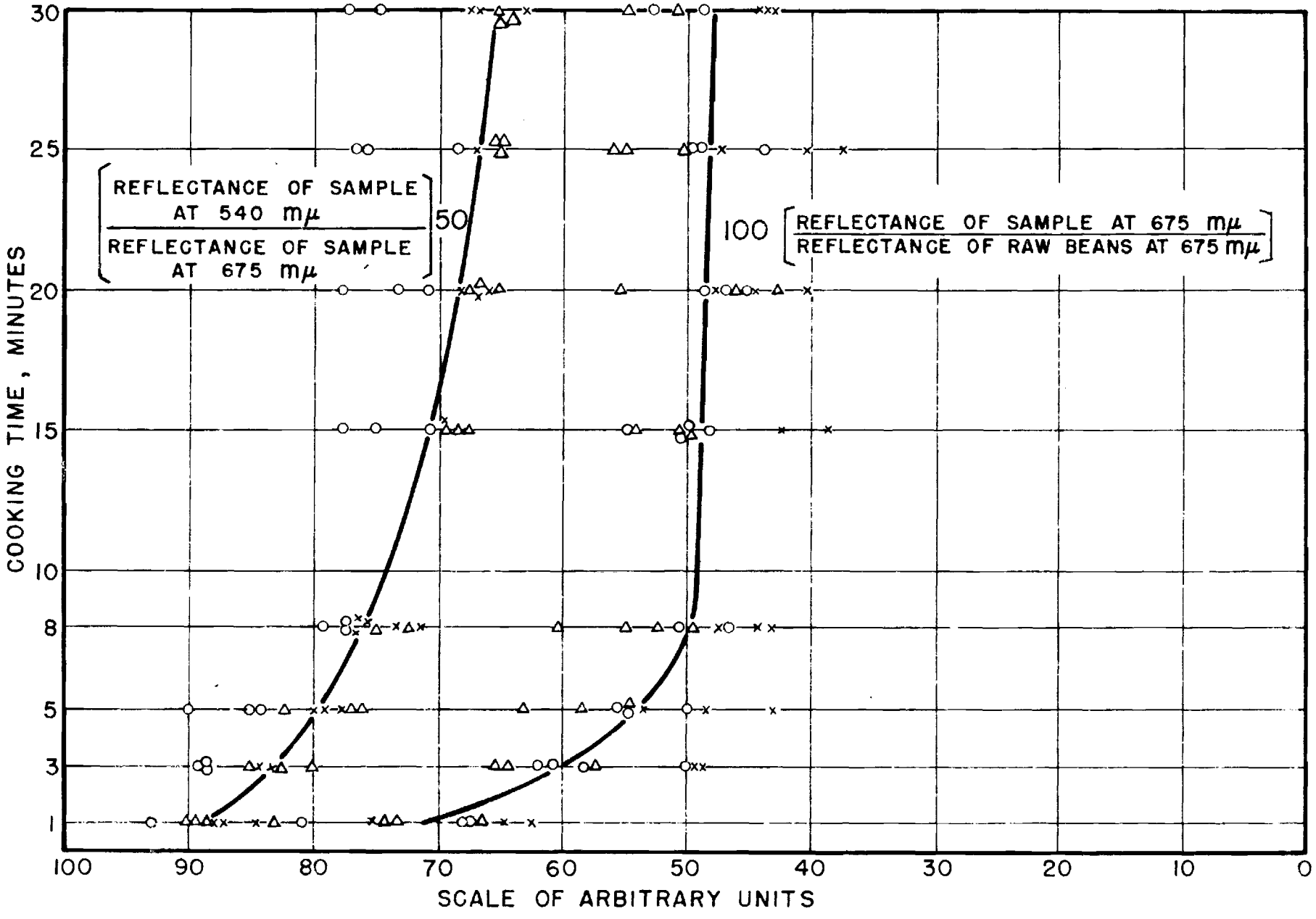

Figure 2. Two Mathematical Statements of the Reflectance Data Obtained From Cooked Green Beans.

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the grouping for the quotient of the 540 reading divided by the 675 reading and the grouping observed in Figure 1, the data for the lot of beans indicated by O clustering away from the data for the other two lots. Since this is contrary to the visual observations reported, the usefulness of this mathematical statement would seem to be doubtful. The data for the ratio of readings made at 675 millimicrons show considerable scattering, although they cluster in the same manner as the data in Figure 1. However, the line indicating the trend of these ratios shows a marked change in slope between five and eight minutes cooking time—the latter portion of the curve being extremely steep, indicating that these observations would be of no value in characterizing changes in this range.

In the previously reported work (3) on methods of mathematically characterizing the profile of the color curve, it was noted that one such method as employed by Lott (4) for the analysis of the reflectance curves obtained from apples seemed to be valuable, although the observations available at that time were insufficient to verify this conclusion. The technique employed by Lott was essentially that of characterizing the size of the valley associated with the 675 millimicron reading (chlorophyll) on the color curve. This was done because the readings made in the green portion of the spectrum tended to rise rapidly as the apples being examined matured, thus causing a deepening of the valley around the 675 millimicron reading. However, the color curves for green beans showed a gradual diminution of the reading in the green portion of the spectrum which correlates with changes in the color of green beans, and for this reason the area under the green peak was estimated.

As the profile of the reflectance curves previously collected from green beans had shown no great tendency for the location of the peak in the green portion of the spectrum to shift, it was felt that if a color triangle were erected between the 430, 540, and 675 millimicron readings and a trapezoid beneath this from the 430 and 675 readings, the area beneath the curve within the visual region of the spectrum could be approximated. In other words, a summation of the areas of the color triangle and the subjacent trapezoid should yield a mathematical statement which would picture the profile of the reflectance curve.* Such calculations were carried out for a number of observations made on green beans. However, the results did not show a great change in value with corresponding changes in visually observed color changes. This was apparently due to the fact that the area of the trapezoid was always larger than the area of the color triangle, and the area of the trapezoid was determined by the size of the readings at 430 and 675 millimicrons. Reference to Figure 1 shows that these two observations picture a much lower rate of change with cooking time than do the observations at 540 millimicrons.

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*The area beneath the curve formed by the 430, 540, and 675 millimicron readings can be estimated most easily if these points are placed on X and Y axes; the wavelength of the light being on the X axis and the per cent reflectance being on the Y axis, and 430 millimicrons being set equal to zero. The reflectance at 430 millimicrons then becomes Y_3; that at 540 millimicrons, Y_2; and that at 675 millimicrons, Y_1. The equation for the area of the color triangle is then equal to: $1/2(245Y_2 + 110Y_3 + 0 - 245Y_3 - 110Y_1 - 0)$, while the area under the trapezoid formed by the reflectance readings at 430 and 675 millimicrons is equal to: $1/2(245)(Y_1 + Y_3)$. The sum of these two equations then simplifies to: 122.5 [(0.45)(reflectance at 430 mμ) + (reflectance at 540 mμ) + (0.55)(reflectance at 675 mμ)]. The constant value 122.5 has been deleted in this work.

It had been noted (3) that the reading at 675 millimicrons tended to correlate linearly with the I.C.I. values for per cent brightness. If brightness is a characteristic of a color which can be disassociated from the hue and chroma, a mathematical treatment removing brightness from consideration (leaving only hue and chroma) might be of value in characterizing color changes in green beans. The previously observed correlation of the 675 millimicron reading with brightness (3) indicated a justification for the use of this reading as a substitute for brightness in such calculations. In short, the area of the color triangles** (that is, the triangle formed between the points determined by the readings at 430, 540, and 675 millimicrons) would be such an index. Such calculations were carried out on the data from cooked beans and are shown in Figure 3.

The curve shown in Figure 3 was constructed in a manner similar to that employed for Figures 1 and 2. It will be noted that the data represented by X tend to cluster away from the data represented by either O or Δ, agreeing with the visual report on these three lots of green beans. The curve shown in Figure 3 not only agrees with the reported visual observations but also seems to have good linear correlation with the color changes in green beans caused by cooking. It would thus appear that the estimation of the area inside the color triangle is a valuable index for characterizing color changes in green beans.

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**The equation for the area of the color triangle simplifies to: 122.5 [-(0.55)(per cent reflectance at 430 mμ) + (per cent reflectance at 540 mμ) - (0.45)(per cent reflectance at 675 mμ)]. The constant value 122.5 has been deleted in this work.

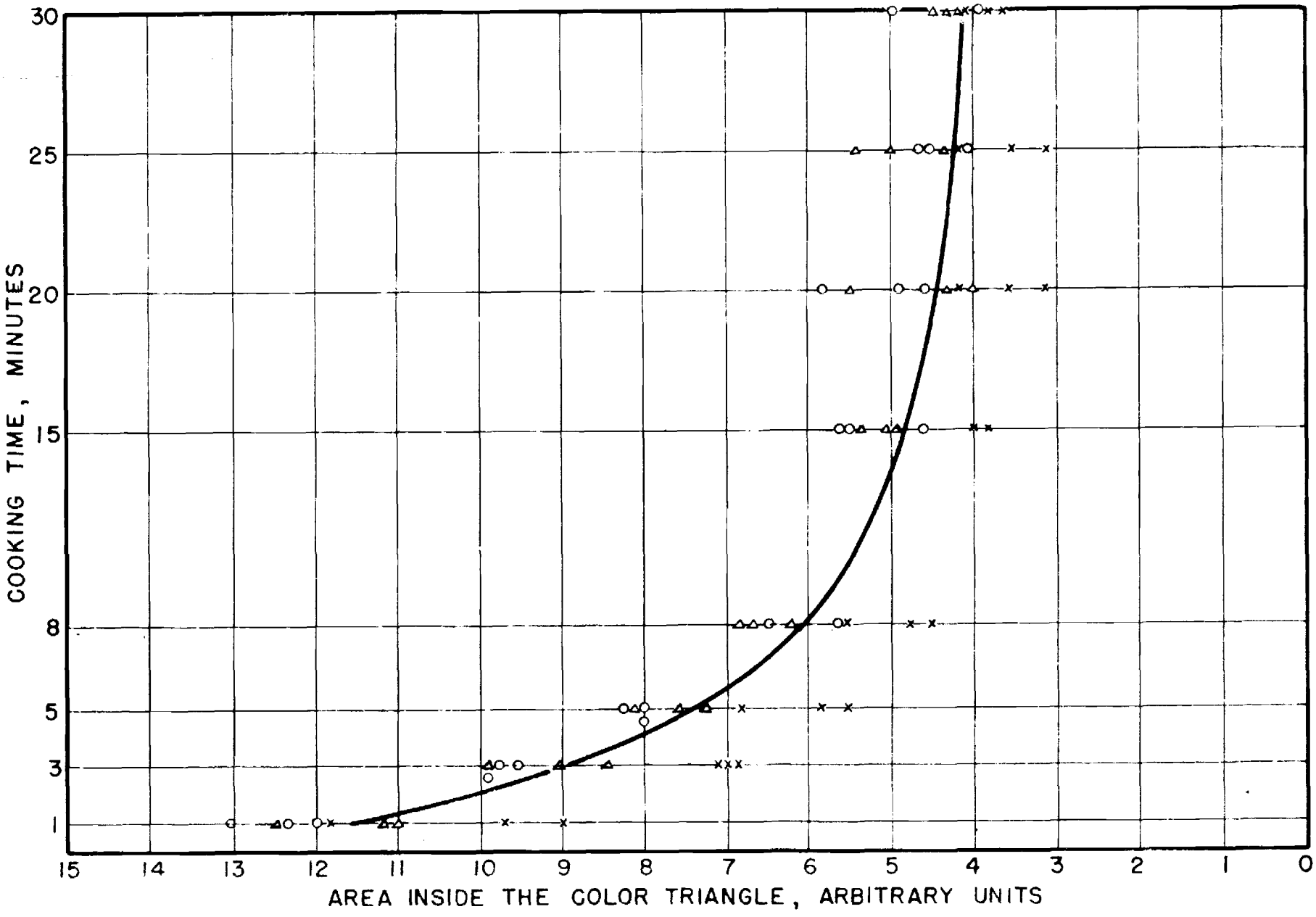

Figure 3. Reflectance Data From Cooked Green Beans Expressed as the Area Inside the Color Triangle.

In order to evaluate the significance of the values recorded in Figure 3, the mean and standard errors of the areas inside the color triangles are shown in Table I. As the data from lot D appear to be different from those for lots E and F, pooled averages for lots E and F are also given in this table; Figure 4 represents these data graphically.*** Analysis of these data show that a significant difference exists between the mean areas inside the color triangle for beans cooked one, three, five, eight, or fifteen minutes. No such significant difference exists between the values for beans cooked fifteen, twenty, or twenty-five minutes, although a real difference exists between the values for beans cooked fifteen or thirty minutes.

The reported visual observations on cooked beans had indicated a slight but perceptible difference between the color of beans cooked twenty or thirty minutes. It would thus appear that the trained observer is more capable of distinguishing slight color differences than any of the methods of color analysis presented in this work. However, instrumental analysis of color is capable of color "memory." This trait is almost nonexistant in human beings, so that instrumental analysis makes possible the study of color changes that take place over periods of days and months. Because of this, and the other good features of the area inside the color triangle as an index of color change on green beans, it was decided to employ this mathematical statement for such a

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***The equation for the curve shown in Figure 4 is:

$$X = 11.95 + 0.061Y - 6.37 \log Y$$

where X = area inside the color triangle, and Y = time of cooking.

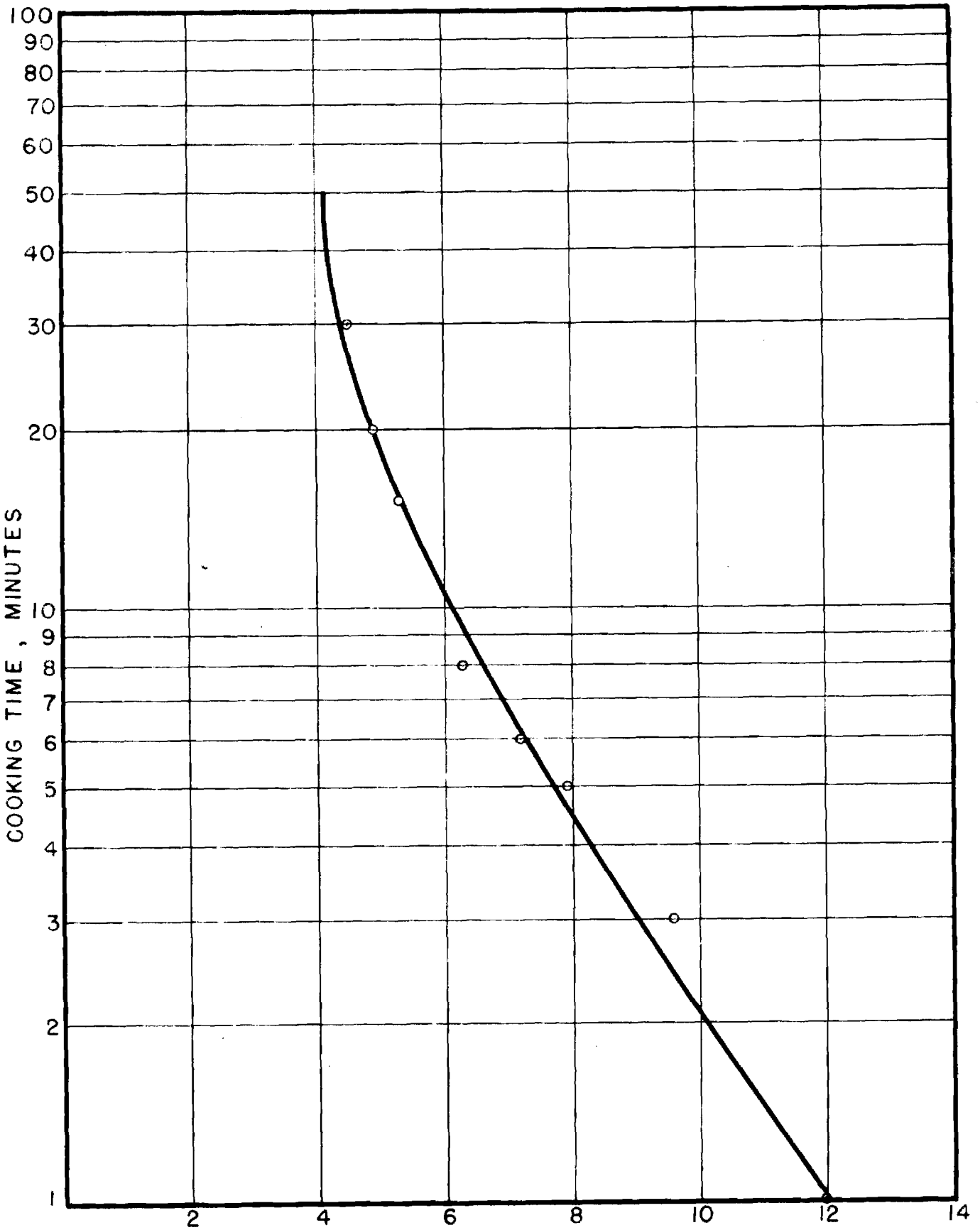

Figure 4. The Relation Between the Area Inside the Color Triangle and Cooking Time For Green Beans.

TABLE I

REFLECTANCE DATA OBTAINED FROM COOKED GREEN BEANS, EXPRESSED AS THE AREA INSIDE THE COLOR TRIANGLE*

Time of Cooking	Average** Area (±Standard Error) Inside the Color Triangle			
	Lot D	Lot E	Lot F	Lot E plus Lot F
1	10.22±0.841	12.51±0.310	11.59±0.524	12.05±0.318
3	7.03±0.073	9.81±0.105	9.40±0.455	9.60±0.265
5	6.10±0.118	8.13±0.061	7.67±0.248	7.90±0.153
8	4.97±0.335	6.09±0.241	6.64±0.186	6.26±0.171
15	4.28±0.400	5.34±0.305	5.13±0.133	5.23±0.151
20	3.68±0.292	5.20±0.294	4.62±0.450	4.91±0.279
25	3.65±0.320	4.45±0.185	4.89±0.301	4.67±0.187
30	3.88±0.103	4.49±0.490	4.43±0.057	4.46±0.159

*Determined by deleting the constant 122.5 from the equation, the area inside the color triangle is equal to:
(122.5) [(per cent reflectance at 540 mμ) - (0.55)(per cent reflectance at 430 mμ) - (0.45)(per cent reflectance at 675 mμ)] .

**For five separate samples each.

purpose in the study of color changes in green beans caused by factors other than cooking.

APPLICATION OF THE DERIVED INDEX

To obtain well established values for the color of green beans in the most common conditions associated with the freezing preservation of foods, a study was made on green beans in the conditions listed in Table II. It can be seen that the area inside the color triangle for raw beans in lots A and B are essentially identical, whereas that for lot C is significantly different, both for fresh and for two-day-old beans. Reported visual observations on the beans agreed with these findings. However, it is to be noted that the data obtained from the processed beans are essentially identical for all three lots. This is also in agreement with the reported visual observations. In general, the data in Table II serve to confirm the value of the area inside the color triangle as an index of the color of green beans.

Values for the area of the color triangle for table grade (edible) green beans in various stages of maturity are shown in Table III. It was not possible to obtain large, properly graded samples for this particular experiment. As a result, the selection of beans according to size (presumably a function of maturity) was relative, and therefore the beans examined as "medium" were not necessarily the same size or maturity in both lots G and H. However, the area inside the color triangle does serve as an index of color difference in several instances. The values for the small beans were similar in both lots and smaller than those for the large beans, which were also similar in both lots.

TABLE II

REFLECTANCE DATA OBTAINED FROM RAW AND PROCESSED GREEN BEANS EXPRESSED AS THE AREA INSIDE THE COLOR TRIANGLE*

Condition of Beans	Lot No.	Average** Area (± Standard Error) Inside the Color Triangle		
		Raw Beans	Blanched Beans	Blanched, Frozen, and Thawed Beans
Fresh	A	18.57±0.219	6.93±0.375	8.33±0.393
Fresh	B	18.07±0.973	6.75±0.889	8.06±0.072
Fresh	C	16.74±0.367	7.60±0.363	6.34±0.227
Two days old	A	19.35±1.733	6.53±0.276	7.83±0.489
Two days old	B	20.25±0.799	7.21±0.274	7.48±0.212
Two days old	C	16.8±0.362	6.32±0.492	6.30±0.324

*Determined by deleting the constant 122.5 from the equation, the area inside the color triangle is equal to:
(122.5) [per cent reflectance at 540 mμ) - (0.55)(per cent reflectance at 430 mμ) - (0.45)(per cent reflectance at 675 mμ)] .

**For five separate samples each.

TABLE III

REFLECTANCE DATA OBTAINED FROM VARIOUS SIZE RAW GREEN BEANS EXPRESSED AS THE AREA INSIDE THE COLOR TRIANGLE*

Relative Size of Green Beans	Average** Area (± Standard Error) Inside The Color Triangle	
	Lot G	Lot H
Small	14.95±0.189	15.59±0.490
Medium	16.62±0.211	19.30±0.240
Large	17.60±0.142	18.58±0.475

*See Table I.
**For five separate samples.

The general indication of the data in Table III is that the size of the values for the area of the color curve for green beans increases with maturity. The evidence from the study of cooked green beans indicates that degenerative changes cause a reversal of this trend. In Table IV values are presented for the areas inside the color triangles obtained from green beans which had been blanched, frozen while fresh, and then stored for various periods of time at $0^{\circ} \pm 0.5^{\circ}$ F. A significant difference exists between the values shown for beans stored two months and those for beans stored 12 months; none exists between the values shown for those stored 12 months and for those stored 24 months; but a significant difference is again found to exist between the values for those stored 24 and for those stored 39 months. In addition to the areas inside the color triangle, the color equivalents in terms of cooking time are also presented in Table IV. These values were obtained from Figure 4, and show the possibilities inherent in the application of the color equivalent in terms of cooking time to the description of the condition of stored frozen green beans.

The use of an index for the color of green beans in terms of equivalent cooking time appears to be of great value in the standardization of the color description of green vegetables. A curve, such as shown in Figure 4, can be constructed by any group of workers and used as a standard in describing the color changes which take place in the green vegetables following processing and storage, whether the processing be freezing or canning. The fact that degenerative changes in the color of frozen green beans caused by storage can be described in terms of

equivalent cooking times makes it possible for workers in the field of the preservation of foods to compare their results on the color changes of green vegetables directly with those of other workers, and to keep comparable records of their own work from year to year. Obviously, a more simple method is necessary for the collection of the essential colorimetric data for estimating the area inside the color triangle; however, with beans cooked various lengths of time used as standards, visual comparison could be made without instruments. Such a procedure would make possible more exact observations on the color changes occuring in processed vegetables than are now being made. It should be noted that Munsell chips could be substituted for the standard beans, particularly if both the chips and the sample of beans were rotated side by side for visual comparison.

TABLE IV

REFLECTANCE DATA OBTAINED FROM STORED FORZEN GREEN BEANS EXPRESSED AS THE AREA INSIDE THE COLOR TRIANGLE*

Length of Storage (months)	Average** Area (±Standard Error) Inside Color Triangle	Color Equivalent in Cooking Time***
2	6.53±0.345	7
12	5.10±0.128	16
24	5.38±0.201	13
39	4.04±0.154	> 30

*See Table I.
**For five separate samples.
***From Figure 4.

SUMMARY

As a result of studies made on the color of the intact surface of green beans with a rotating disc being used to integrate the color of the samples, a numerical index has been derived to characterize the color changes which occur in green beans during maturation and processing. This index is based on reflectance readings made at three wavelengths--430, 540, and 675 millimicrons--and is a function of the area inside the triangle formed by a plot of such data. Furthermore, it has been found that cooking green beans for various lengths of time produces samples which have undergone a series of color changes similar to those caused by freezing storage of beans. Such a series of samples can be employed as color standards for the more exact recording of color changes due to processing, either by visual examination or by reflectance analysis of the color in terms of the areas inside the color triangle. In the latter instance, the data obtained from the cooked samples can be employed to establish a standard curve which can be used to express color changes caused by processing in terms of cooking time.

Although the experimental work reported dealt exclusively with green beans, the results are directly applicable to most green vegetables; the general procedure is applicable to the analysis of the color of the intact surface of practically all foods, and possibly to many other colored materials.

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PROGRESS REPORT NO. 24

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FOOD PRESERVATION

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TENNESSEE VALLEY AUTHORITY

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I. SUMMARY

During the period covered by this report all of the equipment used for color analysis has been overhauled and a study of commercially available equipment of this type has been made. Experimental results previously reported have been assembled in the proper form for publication. A portion of this material is complete and is attached to this report.

II. FUTURE WORK

It is planned to continue the developmental work on a simplified reflectance meter for the analysis of the color of green beans.

Respectfully submitted:

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Approved

Gerald A. Rosselot, Director
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III. APPENDIX

METHODS FOR CALUCLATING FREEZING TIMES FOR FOODS*

I. Freezing Foods in No. 10 Cans

By: T. W. Kethley, W. B. Cown, and F. Bellinger
Georgia Institute of Technology

The results of experimental work at Georgia Tech on the estimation of the time-temperature relations involved in the freezing of foods are directly applicable to the calculation of the time required to freeze various foods under different conditions. Certain of the mathematical techniques required for this application were discussed in a previous publication.[2] However, it has been felt that widespread use of the graphical method of estimating time-temperature relations in the freezing of foods is not practical because of the complexity of the variables involved and the special knowledge required. For this reason it has been planned to present data for specific conditions which can be utilized with little or no mathematical effort.

Although the No. 10 can is not too widely employed as a container for freezing foods, the relative simplicity of the case for this container made it a logical choice for initial presentation. Accordingly, Figure 1 is a chart which can be used in calculating the time required to freeze various foods in No. 10 cans. Table I contains the average values for the thermal diffusivity of certain foods; Table II contains the data necessary for the reconstruction of Figure 1 for individual use. It should be noted that Figure 1 has been drawn on two-cycle, semi-logarithmic paper.

The method of estimating the time required to freeze foods in No. 10 cans can best be explained by the solution of the following typical problem.

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*From a project jointly sponsored by the State Engineering Experiment Station of the Georgia Institute of Technology and the Food Processing Section of the Tennessee Valley Authority.

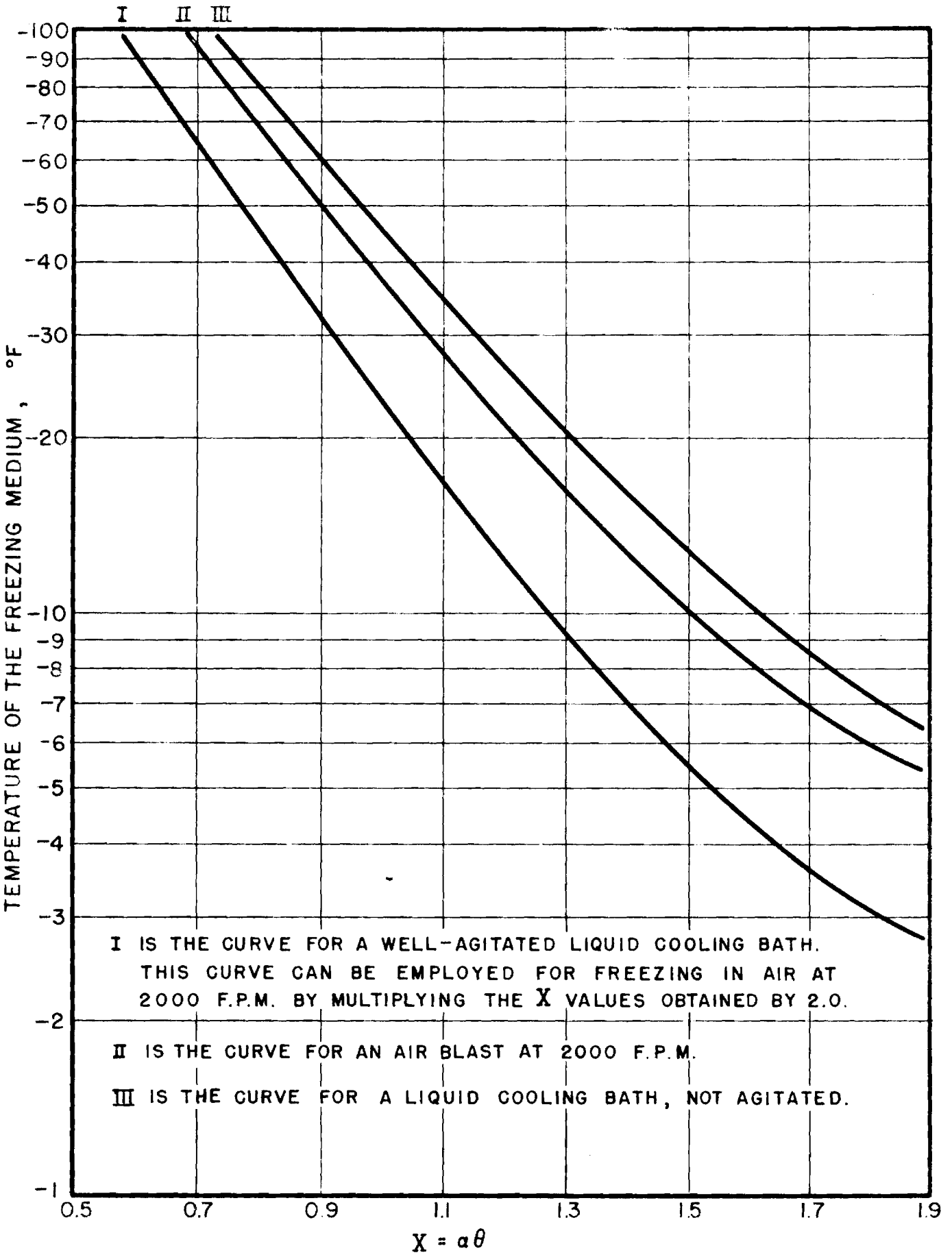

Figure 1. Chart for Estimating the Time Required to Freeze Foods in a No. 10 Can

TABLE I

AVERAGE THERMAL DIFFUSIVITIES (α) FOR CERTAIN FOODS FOR THE TEMPERATURE RANGE, 80°-0° F.

Food	α ft.^{2}/hr.
Apple flesh	0.00580
Blackberries	0.00570
English peas	0.00480
Irish potato flesh	0.00470
Lima beans	0.00480
Peach flesh	0.00465
Strawberries	0.00570
Soy beans	0.00490

TABLE II

DATA FOR RECONSTRUCTING THE CHART FOR ESTIMATING THE TIME REQUIRED TO FREEZE FOODS IN NO. 10 CANS

Temperature, °F.	For Well-Agitated Liquid Bath	For Air, at 2,000 fpm	For Liquid Bath, Not Agitated
-90.2	0.600	0.710	0.750
-31.2	0.900	1.060	1.125
-20.0	1.050	1.238	1.313
-13.6	1.200	1.415	1.500
- 7.0	1.475	1.740	1.840
- 3.4	1.800		

It is desired to know the time required to freeze strawberries in No. 10 cans in a well-agitated bath, the temperature of which is maintained at -20° F. Figure 1 shows that the horizontal line for -20° F. intersects the curve for condition I, a well-agitated liquid bath, at X = 1.05. Simple substitution in the equation

$$\theta = \frac{X}{\alpha} \qquad (1)$$

yields the time in minutes required to freeze strawberries in No. 10 cans under the conditions in question. Thus, α is taken from Table I, and

$$\theta = \frac{1.05}{0.0057} = 184.5 \text{ minutes.}$$

In other words, it requires about three hours and 15 minutes to freeze strawberries in No. 10 cans in a well-agitated cooling bath which is maintained at -20° F.

The only exception to the example cited above is that for the solution of cases involving freezing in air circulating at a linear velocity of 200 fpm. In this instance, the value for X is determined from curve I in Figure 1, and then is multiplied by 2.0 prior to solution for θ.

DISCUSSION

The time-temperature relationships involved in the freezing of food stuffs can be handled best by methods for heat transfer in the unsteady state. Classically, the mathematics of this method are extremely complex; however, graphical solutions are somewhat more simple. The work of Gurney and Lurie[1] and, also, that of Williamson and Adams[4] present this method of approach in some detail. The most available treatment of the graphical analysis of heat transfer in the unsteady state is to be found in McAdams' text on Heat Transmission;[3] consequently, the symbols employed in the present article are those used by McAdams.

In general, the graphical analysis of heat transfer in the unsteady state involves the use of four mathematical statements. These are employed to construct charts from which values can be obtained for the determination of time-temperature relationships in the heating or cooling of a solid:

$$X = \left[\frac{k}{\rho c_p}\right] \frac{\theta}{r_m^2}; \quad \left[\frac{k}{\rho c_p}\right] = \alpha \tag{2}$$

$$Y = \frac{t'-t}{t'-t_b} \tag{3}$$

$$m = \frac{k}{r_m h} \tag{4}$$

$$n = \frac{r}{r_m} \tag{5}$$

The actual charts are constructed by plotting values of X against values of Y with varying values of m or n. As n expresses the position ratio for the solid and is taken to be zero (that is, the center point of the solid) for this work, it need not be considered further. The equation for Y shows that it is the relationship existing between the temperatures of the solid and the bath. The equation for X shows it is determined from the physical constants of the solid and the time involved in the change of the temperature of the solid from its original state to its final state. It should be noted particularly that the three terms in this equation for the physical constants of the solid can be grouped into a single term, α, that is, the thermal diffusivity. The equation for m shows it to be the thermal resistance ratio between the bath and the solid. These equations show that data for X or for Y can be obtained under experimental conditions without too much difficulty. However, the determination of m presents a more complex case. Actually, most of the work which has been done in the engineering application of the graphical analysis of heat transfer in the unsteady state has been for the case: $m = 0$. Conditions for this case can be met only when the solid involved in the heating or cooling is sufficiently large or if the cooling or heating bath has a very high coefficient of heat transfer relative to the surface of the solid.

Reference to the charts found in McAdams,[3] pages 31-37, and consideration of the equations for X, Y, and m will show that it is not possible to construct working curves for the freezing of foods which will cover all the variables involved without a complete knowledge of all the factors involved. These factors include the temperature of the food, the temperature of the cooling medium, the temperature to which the food is to be brought, the size of the food or food package, the coefficient of heat transfer between the food or food package and the cooling medium, the average thermal diffusivity of the food, and the average thermal conductivity of the food. A previous report[2] has shown how the thermal conductivity can be estimated for most food stuffs. Since the numerical size of m varies with the thermal conductivity and physical dimensions of the food for any given conditions of heat transfer, charts such as shown in Figure 1, where only a single size object is considered, are the most practical for everyday use.

However, the potentialities of the graphical method of analysis for the solution of time-temperature problems involved in the freezing of foods for particular cases should not be overlooked. Thus, although the data presented in Figure 1 are for the cooling of foods from 80° to 0° F., this same information can be applied to other temperature ranges. For example, if it is desired to determine the time required to cool foods in No. 10 cans over a temperature range different from this, a value for α can be determined experimentally for this new temperature range by placing a thermocouple in the center of a filled can, immersing the can in the cooling medium, and determining the time required to bring the center of the can to the desired temperature. By employing the arrangement shown

in Figure 1 a new value for α can readily be estimated, since the temperature of the freezing medium, X, and θ will be known. This new value of α could then be used for the calculation of cooling times for the required temperature range.

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